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ORIGIN OF THE ZINC ORES OF SUSSEX COUNTY, N. J.*

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INTRODUCTION.

New Jersey has long ranked second among the zinc-producing states of the Union, the only exception in recent years being in 1916, 1918, and 1920, when Montana took this position. This rank has been maintained by the output of two mines in Sussex County—the one at Mine Hill, near Franklin, and the other at Sterling Hill, near Ogdensburgh, three miles from Franklin. For a number of years preceding 1913 the Sterling Hill mine was idle, but although it has been in operation since then, the output has been small and Mine Hill has maintained New Jersey's rank as a zinc producer. Even though the Mine Hill work-

* Presented in condensed form at the Amherst meeting, December 29, 1921.

ings have been producing heavily since about 1850, they were able, during the recent war, to exceed all previous efforts. In view of these achievements, the Franklin mine must be rated one of the greatest zinc mines in the world.

It may be added that zinc is not the only product of the two mines, for iron and manganese are also recovered and used for making spiegeleisen.

These ore-bodies, aside from their commercial importance, are deservedly famous for their unique mineral composition, and for the great array of minerals making up the ore. The three principal ore minerals—franklinite, willemite, and zincite—are of little importance or unknown elsewhere. The total number of authentic species of minerals reported to date is over one hundred and if we include well-defined varieties (for example, those of the amphibole and pyroxene groups) the number is considerably increased. Of this list, a dozen or more have not been noted elsewhere.[1]

The geology and mineralogy of the deposits have been referred to in more or less detail by many writers through a period of nearly a century and a half, and in recent years the contributions of Kemp, Spencer, Palache, Wolff, and Nason are noteworthy. While these contributions contain many valuable data, no continuous geological record of the district has been kept, and none of the various writers seem to have applied the microscope to the problem of the genesis of the ores. It was hoped therefore that a petrographic study of the ores might throw some light on this puzzling question, and consequently in the present investigation chief emphasis has been laid on this phase of the work. Most of the petrographic work was done by the junior author of this paper.

Through the courtesy of the New Jersey Zinc Company, and with the active coöperation of the officials and the mining staff, such an investigation was made possible. Thanks for many suggestive criticisms are also due to Prof. A. C. Gill. The field

[1] A number of the minerals found have been described in U. S. Geol. Atlas Folio 161, 1908.

work, mostly underground, was carried on during a portion of the summers of 1920 and 1921 as a result of which many specimens for petrographic study were collected from different parts of the mines. The chief object of this paper is to present the results of the laboratory work, with a discussion of their bearing on the genesis of the ore bodies. During the field work, there were also noticed some interesting structural features, not hitherto recorded, and a brief discussion of these is also included.

While an attempt has been made to consider the paragenesis and relationships of all the minerals collected there are certain ones which are found only at relatively rare intervals, and whose exact position in the ore body is not always known, so that little or nothing can be said regarding them. Many interesting specimens were obtained from the picking table, but in the majority of cases it was often impossible to ascertain from just what part of the mine they came. Then too it should be added that some portions of the ore body which have yielded interesting mineral combinations are now worked out, so that from these no geologic data are now obtainable.

STRUCTURAL RELATIONS OF THE ORE BODIES.[2]

The published geologic map in the folio of the Franklin Furnace quadrangle shows that the southeastern portion of the area extends into the "Old Appalachian" province of ancient crystalline rocks, while the remaining portion lies in the "New Appalachian" province of Paleozoic sediments. The boundary between the two groups cannot, in this region, be sharply drawn; instead, we find a zone some miles in width, in which, as a result of repeated faulting, the two groups of rocks alternate in narrow belts and lenticular areas, isolated blocks from each group being found at different distances from the parent masses.

The larger structural features of both provinces conform to a NNE–SSW direction. The major faults and the resulting belts of different formations, the longer axes of the large intrusive

[2] For greater detail than is here given see especially the U. S. Geol. Atlas Folio, no. 161, 1908.

masses, the foliation of the pre-Cambrian rocks, and the strike of the Paleozoic sediments, all show this general trend.

Pre-Cambrian Formations.—These include the highly metamorphosed Franklin limestone and Pochuck gneiss; the Losee and Byram granite-gneisses, and numerous minor intrusions, chiefly pegmatites. These several formations are described in some detail in the Franklin Furnace atlas folio, but by way of summary may be briefly referred to here.

Franklin Limestone.—In the Franklin Furnace quadrangle this limestone is confined to a belt nowhere more than a mile in width, entering the quadrangle at the northeast from Orange County, New York, and after extending some 12 miles in a southwesterly direction, finally wedges out against a fault, already mapped by Spencer.

The limestone is usually glistening white, composed almost entirely of coarse grains of calcite, or sometimes dolomite. At a few points within the mines patches of fine-grained gray limestone were found within the white. They are not the same as certain streaks of fine-grained gray dolomite noted by Spencer[3] and also observed by the writers in certain post-ore fractures.

Pressure twinning is almost universal in the normal crystalline limestone. The composition of the limestone is variable, the rock ranging from pure calcic limestone to dolomite with 20 per cent. or more of MgO. There is no evident regularity in the distribution of the MgO, and the variations in composition do not appear to be correlated with variations in texture of other factors, nor with the presence of intrusive rocks.[4]

Banding or foliation of variable distinctness may be observed in practically every exposure of the limestone, and is noticeable especially in some of the open cuts of the mines at Franklin Furnace, where it is evidently due to carbonaceous matter. In other

[3] *Loc. cit.*, p. 10.

[4] Kümmel, H. B., "Chemical Composition of the White Crystalline Limestones of Sussex and Warren Counties," N. J. Geol. Surv., Ann. Rept. of State Geologist, 1905, pp. 173–191. Also Nason, F. L., *Amer. Geol.*, XIII., pp. 154–164.

cases it may be due to scattered grains of graphite or various silicates. The identity of the planes of foliation with original bedding planes can seldom be established with certainty, but Spencer has noted that where undoubted stratification has been observed, "any foliated effect produced by the presence of silicate minerals is almost invariably parallel with the bedding."[5] The strike of the foliation is parallel to the general structural alignment of the region, and the dip is ordinarily 70–75° E-SE, in accordance with the foliation of the enclosing gneisses; locally, however, as in the vicinity of the Franklin mine, pronounced folding is apparent. Spencer has described some layers of pure limestone and also siliceous beds, which locally permit determination of the bedding in the rock.

The limestone contains a variety of minerals scattered through it, as already mentioned by other writers. Among them may be noted phlogopite, chondrodite, tremolite, diopside, quartz, fluorite, hornblende, scapolite, and occasionally magnetite, sphalerite and garnet.

It is of interest to note that any or all of these may be found in the limestone either remote from or close to the ore-body, and in the latter case it may be difficult to decide whether they represent the product of regional metamorphism of earlier age than the ore minerals, or contact-metamorphic minerals due to post-ore intrusions.

Basic Masses in Franklin Limestone.—At several places in the Franklin limestone there are found masses of dark rock of a schistose or gneissoid structure (Pl. IX., *A*). The chief dark minerals in them may be either hornblende or biotite, while the light-colored minerals include quartz, feldspar, sphene and spinel.

While in many cases these foliated rocks form relatively small fragments, which may occur singly or in strings, they at other times occur as broad bands 10 to 20 feet wide which extend straight away for a distance of several hundred feet. The smaller masses often look as if they had been formed by the breaking up and tearing apart of larger ones.

[5] Spencer, A. C., U. S. Geol. Atlas Folio, 161, p. 3, 1908.

It may be doubtful whether these dark foliated rocks in the limestone represent dikes or beds of impure limestone or shale, which have not only been metamorphosed to their present condition, but also broken up in the deformation which the limestone has evidently undergone. Spencer refers to them as dikes, because some of them show branching forms.

Such foliated basic masses in crystalline limestone have been described by other authors, and various origins have been assigned to them.[6]

Those seen in the large limestone quarry near McAfee for example are in many instances of irregular shape, and consisted chiefly of hornblende and biotite. Much pyrite is scattered through some of them, but seems to show a tendency to be around the margin of the mass. The outer rim of the mass frequently shows coarse hornblende with pyrite and biotite, while next to the hornblende the calcite is sometimes excessively coarse. In this quarry the largest basic mass happens to be very straight and of uniform width, the central portion of it being occupied by bands of pegmatite with indefinite boundaries trending parallel with the banding of the gneiss.

A second basic mass worth noting is to be observed in the open cut of the west vein at Franklin, and beginning about 50 feet north of the large basic dike which cuts across the ore-body This consists of a mass of dark gray gneiss, probably 200 feet long, which strikes parallel with, and forms the hanging wall of the west vein for perhaps 100 feet, while on the east it is bounded by pegmatite. To the north, this mass of gneiss appears to show a rather blunt end with a width of 20–25 feet, while to the south it ends as a narrow wavy tongue in the pegmatite (Fig. 49).

What appears to be the normal gneiss contains hornblende, biotite, quartz, feldspar, and a little sphene. No ore minerals were observed in it.

Pegmatite bands from ¼ inch up to 12 inches in width cut the

[6] See for example, Newland, N. Y. State Museum Bulletin 196, 13th rep. Director, N. Y. State Museum, 1916; Adams and Barlow, Can. Geol. Surv., Mem. 6, 1910.

gneiss obliquely, at right angles, or parallel to the foliation. At one place the pegmatitic juices which penetrated the gneiss developed peculiar eye-like spots referred to under acid pegmatite

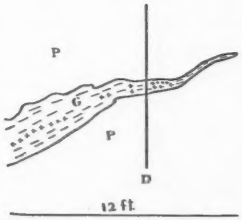

FIG. 49. Pegmatite (*P*) at Mine Hill surrounding tongue of gray gneiss (*G*), with pegmatic material (+), basic dike (*D*) one inch wire cutting both.

and shown in Fig. 49, *D*. The gneiss also contains megascopic garnet either in disseminated grains or as veins cutting across the foliation, but the significance of these is referred to under the pegmatite.

Pochuck Gneiss.—This, as already described by Spencer, is a dark, strongly-foliated rock, consisting of biotite, hornblende and pyroxene as the chief constituents, and oligoclase usually as the only light mineral. According to Spencer there are small amounts of microcline, andesine and labradorite, while some facies contain scapolite. Accessory minerals are magnetite, zircon, sphene and apatite. It forms several large belts within the area of the Franklin Furnace quadrangle, as well as a number of smaller areas. No special examination was made of it except in the immediate vicinity of the ore body at Franklin where it borders the limestone on the northwest. It is also disclosed at the north end of the Mine Hill workings under the cover of sedimentary rocks. The foliation of the gneiss is concordant with that of the limestone.

Whether the Pochuck gneiss was originally an igneous or sedimentary rock has not been definitely settled, the prevailing tendency of recent authors[7] being to regard it as in part igneous and

[7] See Lewis and Kümmel, "The Geology of New Jersey," Bull. 14, N. J. Geol. Surv., 1915, p. 42. Berkey and Rice, *N Y. State Mus. Bull.*, nos. 225, 226, 1921. Spencer, U. S. Geol. Atl. Fol., 161, p. 4, 1908.

in part of sedimentary origin. As a consequence of this uncertainty, the genetic relationship between the limestone and the gneiss is also in doubt. On this point Spencer[8] says:

> Between the two rocks there is a sharply defined and essentially regular surface of contact, which conforms in attitude with the layering in the gneiss. There are, however, no features that would indicate the geologic relation between the gneiss and the limestone.

In the Franklin workings the present writers studied a large number of cross-cuts which crossed the limestone-gneiss boundary. No absolute contacts were found, owing to the presence of pegmatite injected between the two formations. It was clear, however, that the separation was "essentially regular," and it seemed equally clear that it was not an intrusive contact, as there were found no evidences of alteration of the limestone, nor any tongues of gneiss cutting into the latter. Though definite proof was admittedly lacking, the authors feel that the gneiss limestone contact at this point is a sedimentary one. On this assumption, the parallelism of the planes of foliation in both formations with the surface separating them might be explained as due in part, at least, to their original structure as a bedded series.

Losee and Byram Gneisses.—These constitute the largest units of the pre-Cambrian rocks in the quadrangle. They are light-colored, massive rocks, somewhat foliated, and form great elongated masses paralleling the general structure of the region. They are clearly of igneous origin. The Losee is regarded as certainly, and the Byram probably, later than the Franklin Limestone and Pochuck Gneiss. According to Spencer[9] they differ chiefly in the kind of predominating feldspar; that in the Losee gneiss being mainly oligoclase, while that in the Byram gneiss is largely microcline or micro-perthite. The genetic relationships between the two types are not clearly known.

Pegmatite.—As already stated by Spencer pegmatite bodies occur in all parts of the Highlands, either in the gneisses or the Franklin limestone. In the gneisses they may appear as the more

[8] U. S. Geol. Atlas Folio, 161, p. 4.

[9] *Loc. cit.*

coarsely crystalline portions of the surrounding rock, or as well-defined dike-like masses. When thus found in the Pochuck gneiss, as near Franklin, the stringers and bands of pegmatite run chiefly parallel with the foliation, but there are also stringers crossing the foliation at various angles which are at times so numerous as to form a network. A good example of this is seen in an outcrop of Pochuck gneiss on the southern edge of the town of Franklin. In the limestone the pegmatites are clearly defined, except where present in some of the gneissic masses inclosed in the limestones.

In Mine Hill, the pegmatites are all of acid character, but none of this type have thus far been met at Sterling Hill, except that descriptions of the material struck in some bore holes suggest that it may have been composed of such material. It is also significant that at one such point the ore contains garnet, biotite, hornblende, and rhodonite.

Spencer, however, refers to a certain intrusion at Sterling Hill which he calls basic pegmatite, but which so far as its surface exposure is concerned might better be designated as a syenite.

Acid Pegmatite.—This occurs at Mine Hill in masses ranging from stringers and small bunches up to dikes and lenses of large size. It may be divided into two types, as follows: (1) A coarse-grained rock consisting essentially of blue microcline, quartz, garnet, and hornblende. Much of the microcline is typical amazon stone, and crystals up to 3 inches in diameter are of frequent occurrence. This rock is now practically inaccessible in the workings, and its relation to the next type of pegmatite is not known.

Kemp[10] has described an occurrence of it in the Trotter shaft, during the earlier development of the mine.

(2) Pink or gray pegmatite, representing the common type in this region, is encountered in practically every portion of the present Mine Hill workings, but is most abundant in the vicinity of the west limb of the trough. In Mine Hill it shows a somewhat marked tendency to follow the limestone-gneiss contact,

[10] "Ore Deposits at Franklin Furnace," N. Y. Acad. Sci., *Trans.*, vol. XIII., p. 76, 1894.

sending out tongues into both formations, and in some cases even crossing from one to the other.

Plate IX., *C* shows a rather interesting lens-shaped mass of pegmatite in the hanging wall of the "west vein," at Mine Hill, at a point a few feet south of the powder house. It will be noticed that the larger axis of this lens is parallel with the banding of the limestone, and that a narrow fissure extends from both ends of the lens, a continuation, as it were, of the lenticular opening. The pegmatite shows no trace of gneissic structure.

A second interesting case is that shown in Fig. 50, which is a

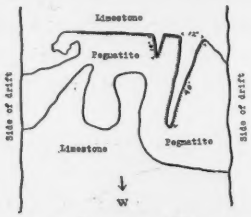

FIG. 50. Sketch of pegmatite intrusion (*D*) in roof of 259 cross cut, 750 level, Mine Hill. Shaded borders represent zone of contact silicates.

sketch of the limestone pegmatite contact exposed in the roof of the 259 cross cut, 750 level. Here the pegmatite which is intrusive in the limestone is bounded by a dark band, ⅛ to ¼ inch wide, which constitutes a narrow zone of contact minerals including pyroxene, epidote, hornblende, quartz, microperthite, microcline and calcite.

The pink or gray pegmatite is characterized chiefly by quartz, gray or pink orthoclase, microcline, albite, and microperthite. It is a more acid rock than the first, and is finer grained, the feldspars rarely exceeding ¾ inch in diameter. Of other minerals, hornblende and pyroxene were found to be present in variable amounts, together with sphene, epidote, garnet and magnetite. Spencer also mentions zircon, allanite, fluorite, graphite and scapolite, but none of these was observed in the sections examined by us. The magnetite is somewhat irregular in its distribution, and ranges from small grains up to masses several feet in diam-

PLATE

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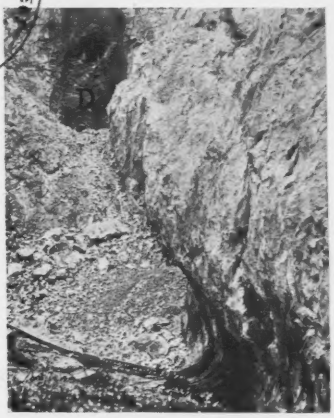
A



B

C

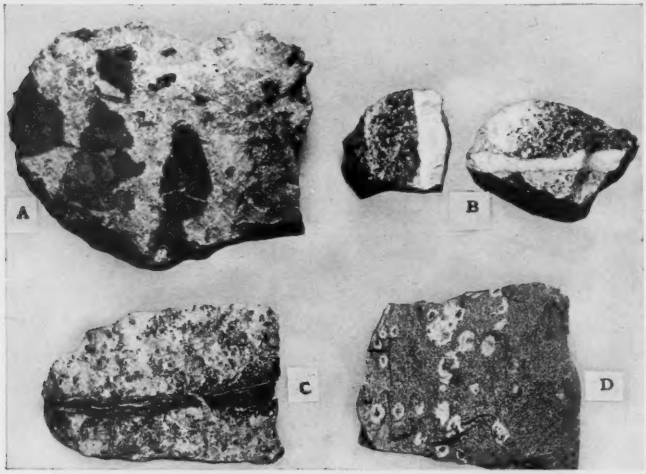
D

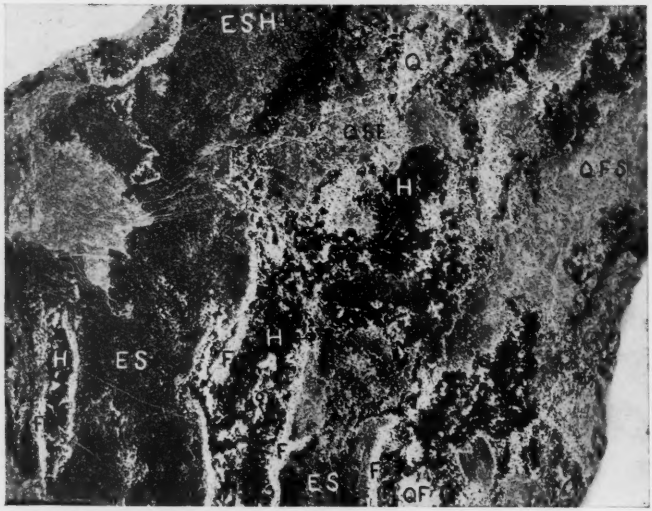
A. Looking south in open cut at southern end of Mine Hill, Franklin, N. J. Schistose basic mass in white limestone, with basic post-Ordovician dike cutting both rocks.

B. Looking north in same cut. Bottom of pitching trough in foreground. Dark rock at back (*D*) is large camptonite dike cutting across basin.

C. Lens of pegmatite (broken lines) in limestone hanging wall of west limb, Mine Hill. Note fracture extending from both ends.

D. Looking south in open cut along east limb, Mine Hill. The roof of stope remains in two places, showing rounded top of ore, and also pitch of same to northward.





E

A. Breccia, 180 level, north of Palmer shaft; dark fragments, Kittatinny limestone; white, calcite filling; dark spots in calcite are sphalerite.

B. Veins of secondary willemite in normal ore. Dark center of one vein is carbonates of lime and possibly manganese.

C. Post-ore veinlet of opaline silica cutting ore.

D. Eyes of pegmatitic material in gneiss from open cut, Trotter mine, west limb, Mine Hill.

E. Polished slab from syenite-monzonite contact zone, 1600 level, Sterling Hill. *Q*, quartz; *F*, feldspar; *H*, hornblende; *S*, sphene; *E*, epidote.

eter. One section showed rounded grains of magnetite with curious frayed edges (Plate XIII., *F*) due presumably to resorption. These grains were surrounded wholly or partly by rims of garnet, pyroxene, sphene or albite, into which the fringes from the magnetite extended.

An interesting development of magnetite and garnet is found in a large lenticular mass of the pegmatite which has an estimated length of 300 feet and a maximum width of 100 feet, which has invaded the ore along several lines so as to split it longitudinally into three branches. This occurs along the "west vein" at Mine Hill, just north of the large east-west basic dike. In the west portion of this pegmatite is the mass of gray gneiss already referred to and which lies just next the hanging side of the west vein at this point.

Grains of garnet and magnetite are scattered through the pegmatite, a good many of the magnetites being as much as an inch in diameter. On the south side of the opening about 50 feet north of the east-west basic dike there is a large crescent-shaped mass, probably 3 feet in diameter, which consists of almost massive magnetite containing streaks of garnet. The boundaries of this mass are not perfectly sharp. Near this are small streaks of magnetite, one of which has a rim of garnet. Farther up the face of the exposure the pegmatite is full of magnetite spots up to two inches in diameter. These two minerals are considered to be original minerals of the pegmatite, for magnetite at least is a wide spread constituent of it.

Contact Effects of Pink Acid Pegmatite.—The intrusion of the pegmatite was evidently accompanied by the injection of juices which produced irregular and interesting effects, among which are those produced on the white limestone, the ore, and the gray gneiss included within the pegmatite in the west vein. The chief effect of the pegmatite on the limestone appears to be the development, locally, of contact-metamorphic minerals replacing the limestone.

These minerals may form narrow rims, along the pegmatite border, not more than one eighth to one fourth of an inch wide,

or at other places there may be developed zones of what are probably completely replaced limestone, several feet thick, the minerals forming these zones being mainly garnet, less abundantly pyrite, and not at all uncommonly, so far as the writer's observations go, such minerals as hornblende, pyroxene, and epidote. Spencer mentions a number of others which he classes as contact-metamorphic products.

The contact rims shown in Fig. 50, for example, have been already mentioned and there is no ore in contact with these.

The effect of the pegmatite on one of the gneissic bands in limestone, as shown by a megascopic and microscopic study of the occurrence from the hanging wall of the west limb just north of the large basic cross dike, is peculiarly interesting, for here the pegmatite not only cuts through the gneiss in various directions, but the juices seemed in places to have pretty thoroughly saturated the gneiss. Indeed it is possible to collect specimens showing all gradations from the normal gneiss to those which are largely quartz-feldspar mixtures, with very few of the dark silicates remaining. As a result of the pegmatite juices soaking into the gneiss, garnet has been especially abundantly developed either in the form of disseminated grains, or sometimes as solid veinlets which may run either parallel with or at right angles to the foliation of the gneiss. Sphene, green spinel, hornblende, and magnetite are likewise abundant in some thin sections of the invaded rock.

In one part of the gneiss there are numerous eyes ¼ to ½ inch in diameter (Plate X., *D*) with dark centers. The light-colored outer rim consists chiefly of a fine-grained mixture of quartz and albite, while the center consists of a fine-grained intergrowth of biotite, deep green spinel, and small amounts of albite and quartz. Around the margin of this central part are lavender-colored grains of tourmaline. The appearance and mineral composition of the eye-like structures suggests that they may have been formed by the action of more volatile material from the pegmatite collecting either in miarolitic cavities or at loci of reduced pressure.

The effect of the pegmatite intrusion on the ore minerals has been brought out by Spencer in his work on the Franklin ores. Briefly stated, his view is that the juices from the pegmatite have reacted with the zinc ore minerals (which he thus rightly regards as of pre-pegmatitic age) and have not only developed zinc and manganese-bearing silicates, but have also caused some recrystallization of the ore minerals themselves.

The reaction between ore minerals and pegmatitic emanations seems to be indicated by the occurrence of rhodonite, hardystonite, leucophœnicite, jeffersonite, gahnite, and garnet (variety polyadelphite) in the vicinity of the pegmatite-ore contact, and not in other parts of the Mine Hill ore-body. At Sterling Hill, they are also limited to one such contact.

Confirmatory evidence was found by the authors in some thin sections, where the silicates from the pegmatite had evidently attacked some of the ore minerals such as willemite and franklinite.

The second point, namely the recrystallization of the ore minerals, is not as susceptible of proof, and the writers are inclined to believe that it is not quite as wide spread as Spencer seems to think.

There is a strong possibility, however, that such a change may have taken place to a limited extent, for the reason that while the paragenesis of the zinc-ore minerals outlined on a subsequent page seems to hold good throughout the two ore bodies, in two or three sections from Mine Hill, which showed both the ore minerals and contact silicates, there was some franklinite and zincite which seemed to be later than the silicates.

Spencer has also suggested that the secondary vein-willemite, and even the sphalerite may be due to the action of the pegmatite emanations on the primary zinc-ore minerals, but the authors are inclined to doubt this, especially in so far as it relates to the sphalerite.

Basic Pegmatite.—Spencer states that at Sterling Hill[11] there occurs a dike of hornblende pegmatite, which lies inside the

[11] *Loc. cit.*, p. 7.

trough of the ore and is "separated from it by a few feet of barren marble or very lean ore." It curves around with the ore body, being "about 300 feet long on the western and 700 feet long on the eastern leg, and from 2 to 30 feet wide. The wall of this dike on the side next the ore carries the unusual manganese and zinc-bearing silicates which the mine affords."

Unfortunately this rock is not accessible below ground at the present time, and the only exposure of it is in the old Calamine pit. Here it is not sufficiently coarse-grained to be designated a pegmatite in the ordinary field significance of that term, and one thin section examined indicates that it is to be classed as a syenite. It shows a foliated structure, and the fresh rock consists of orthoclase, a small amount of oligoclase, much green hornblende, and lesser amounts of biotite, sphene, and apatite. The biotite appears to be secondary as long crystals of it cut across the other minerals. In the open cut it shows an irregular contact along its eastern boundary with the Franklin limestone, and there is an intervening zone of pyroxene, garnet, and biotite from 2 to 3 feet wide.

The limestone next to this is coarse-grained and filled with hornblende patches some of which are 6 inches across. This coarse material is by no means present all along the contact, the mineralized zone in places being very slight, while for most of the distance in the pit, normal limestone extends right up to the syenite boundary.

Spencer believes that this dike postdates the ore because of the manganese and zinc-bearing minerals in the contact towards the ore, but antedates the period of folding because it curves with the ore.

Syenite-Monzonite and its Contact Zone.—In the roof of a raise ending at the 1,600 level in Sterling Hill, there is a mass of indistinctly banded rock, which can be traced definitely as far down as the 1,680 level. The banding which is more noticeable when viewed in a large mass than in the hand specimen is at right angles to the strike of the east limb of the basin, and may be a flow structure.

This rock consists chiefly of acid plagioclase (oligoclase), orthoclase, green hornblende, and sphene with lesser amounts of biotite and epidote. The feldspar shows alteration to a fine-grained mineral, probably sericite. It is to be classed as a syenite-monzonite.

At the top of the raise, along the cross cut on the 1,600 level, the roof shows much quartz, and silicates, with an indistinct banded structure (Plate X., *E*). This mass is mostly rather fine-grained and in places is of bright green color due to abundant epidote but contains bands of hornblende ¼ to ½ inch wide together with irregular bands of feldspar and irregular but often elongated patches of quartz. The quartz in places seems to represent cavity filling, and is sometimes bordered by heavy rims of hornblende which have a zigzag boundary. On the wall of the cross cut at top of raise the white limestone contains large pieces of very coarse hornblende with some garnet. In places the hornblende shows crystal outlines, and contains small grains of unreplaced calcite.

While the limestone in most places shows the normal texture, areas of it several feet in diameter may be very fine-grained.

The fine-grained portions of the mass exposed in roof of the cross cut show a mixture of calcite, pyroxene, hornblende, sphene, garnet, epidote, quartz, albite, orthoclase, and microcline; the epidote in portions of the mass being so abundant as to color the rock green. The quartz appears to be about the last mineral introduced and is usually in more or less separate patches. The feldspar follows bands of hornblende and sometimes cuts them. It seems to have replaced the hornblende because on either side of these veins there are minute grains of feldspar often of rhombic shape, which appear to represent a replacement of the dark silicate (Plate XII., *A*).

The pyroxene in some grains shows alteration to serpentine and a part of the epidote appears to be also an alteration product of either the pyroxene or hornblende. Garnet is also present in the mass, but it is not abundant. The sphene appears to have formed earlier than the epidote and albite.

Three metallic minerals, franklinite, sphalerite and pyrite, were noted in small amounts in this rock, which is regarded as a contact-metamorphic zone of the syenite-monzonite. The first named may be simply grains of ore mineral which antedate the syenite-monzonite intrusion. They were noticed in association with the garnet, which surrounds the franklinite and extends into it in the form of veinlets. A variation of the veinlet structure is seen in trains of small disconnected rectangular garnet grains in the ore mineral. These occur in places by themselves, and in other places form a continuation of the garnet veinlets. The garnet is therefore clearly later than the franklinite.

Both the pyrite and sphalerite which occur sparingly in small scattered grains appear to be later than the silicates.

Paleozoic Formations.—Cambro-Ordovician sediments rest unconformably upon the older rocks or in places are faulted down against them. The former may be seen to good advantage on the west side of the main belt of Franklin limestone. Here the sediments dip 40 to 45 degrees W-NW, while the foliation of the rocks upon which they rest has an opposite dip of 70 to 75 degrees. At the southwestern extremity of the limestone belt, the Pochuck gneiss outcrops between the Cambrian sediments and the Franklin limestone. Passing northeasterly we find the sediments gradually encroaching upon the gneiss, until at Franklin the latter is completely covered, and the stratified rocks overlap the western portion of Franklin limestone and the enclosed ore-body.

Hardyston Quartzite.—This, the oldest of the sedimentary rocks, is typically a quartzite, but locally may be a conglomerate. Its thickness with the limits of the quadrangle varies from a few feet to 30 feet.[12]

Kittatinny Limestone.—The quartzite grades upward into the Kittatinny Limestone of Cambro-Ordovician age. This is a blue, magnesian limestone, often containing numerous vugs filled with calcite and dolomite. Kümmel[13] gives its estimated thickness as 2,500–3,000 feet.

[12] Kümmel, U. S. Geol. Atlas Folio, 161, p. 10.

[13] Loc. cit., p. 11.

On the geologic map of the Franklin Furnace quadrangle, the Hardyston quartzite is mapped as forming a continuous belt immediately west of Franklin Furnace. While much of this has probably been inferred, on account of a heavy drift cover, recent developments in the mines have shown that it is locally cut out by a fault a short distance north of the Palmer shaft.

Basic Dikes.—Some at least of known post-Ordovician age were observed in the Sterling Hill mine, and at Franklin many of them cut the ore (Plate IX., *A, B*). Some of these are well exposed in the walls of the open pit at the south end of the Mine Hill workings. The largest has a thickness of twenty to forty feet, dips vertically and cuts square across the fold of the ore-body, at a point 2,100 feet south of Parker shaft. Wolff describes these dikes in the Geologic Atlas Folio,[14] where he names them camptonites. They have exerted little or no effect on the ore-body, and had nothing to do with the origin of the ore.

THE ORE-BODIES.

The ore-bodies are found in the southwest portion of the belt of Franklin limestone at Mine Hill near Franklin, and Sterling Hill near Ogdensburgh. The outcrop of the limestone formation at both localities is not over one half mile in width, and at both places is bounded on the northwest by the Pochuck gneiss, while on the southeast (Spencer) it is cut off by a fault, along which the Paleozoic sediments have been thrown down into contact with the older limestone.

Both deposits have the general form of synclinal folds plunging steeply NNE (Plate IX., *B*). In each case the east limb is overturned; and the two limbs are unequally developed, resulting in a hook-shaped outcrop. The Franklin Furnace Special Map in the Folio brings out clearly this latter feature, and also shows well the general relationships of the ore-bodies to the country rocks and to the main structural features of the region. Since this report was published much additional mining has been done, showing that some of the earlier views regarding the form of

[14] U. S. Geol. Atlas Fol., 161, p. 13.

the ore-bodies, especially that at Sterling Hill, were not altogether correct.

Mine Hill.

The Mine Hill ore-body lies near the western margin of the Franklin limestone belt, within 20–50 feet of the contact of the latter with the gneiss. The west limb of the deposit is parallel with the general trend of the contact, and with the banding of the gneiss.

The east limb is developed to a much less extent than the other, and after outcropping for about 600 feet its top pitches downward more steeply than the axis of the fold, with the result that in the northernmost portion of the deposit this limb is entirely missing. The west limb outcrops for about 2,600 feet, but further north it is covered by the overlapping Hardyston quartzite and Kittatinny limestone. The general structure just described is brought out in the stereogram shown in Fig. 11, of U. S. Geologic Atlas, Folio 161. Later developments indicate that the west limb shortens to the north and assumes a more vertical position where it is covered by the Paleozoic sediments, while the lower portion thickens still more. There is no sudden termination of the ore, however, and in fact it extends northward to different distances on the different levels.

Different opinions have been expressed regarding the structure of the east limb. Kemp[15] gives a sketch of the ore-body, in which the east limb of the trough is shown as being bent over on itself, thus forming a compressed, pitching anticline. This part of the mine is worked out now, and has been for some time, so that no evidence on that point is now obtainable. His statement appears to be based partly on the fact that the top of the east limb where it pitches under the cover of white limestone is rounded as though it had been folded (Plate IX., *D*), and partly on a statement contained in an unprinted thesis by Woolson and Bemis written in 1886. These writers advance the view expressed above, and as evidence of it state that a rich streak of zincite which

[15] "Ore Deposits at Franklin Furnace," N. Y. Acad. Sci., *Trans.*, vol. XIII., p. 76, 1893.

was found on the foot wall of the west limb is found infolded in the center of the supposed fold formed in the east limb. They also state that there were cracks filled with willemite radiating upward from the top of the supposed fold.

While the ore in this fold has been worked out, the arched top of the stope from which it was removed has recently been exposed in connection with the removal of the limestone for filling in the old workings (Plate IX., *D*). This exposure at present shows no radiating cracks in the roof of the stope. On either side of the opening the banding of the limestone can be seen to extend upwards, the two sets of bands converging slightly as they get above the level of the roof of the stope, but they do not form a connected curve over the top of it.

Nason[16] in a paper giving the results of borings at Mine Hill also expressed the belief that the pitching east limb of the basin is a collapsed anticline, and bases this view partly on the rounded top of the ore-body and partly on the fact that the east limb is almost double the thickness of the west one. He indicates a downward tongue-like extension of the ore-body on the east side of the east vein, but later mining does not seem to have proven the existence of this.

Spencer[17] makes no reference to such a possible folding of the east limb. He does, however, state that while the west boundary of the east limb is indefinite, the ore terminates sharply on the east side, and suggests that it may be cut off there by a fault.

There is no sign of sheeted structure in the rock on the east side of the east limb, such as is found along the fault on the east side of the east limb at Sterling Hill. The hanging wall of this limb does however, in places, show a slickensided appearance. This, however, is not necessarily proof of a large fault, and moreover if the ore-body had been cut off on that side, the fault plane must have been exceedingly irregular.

In the bottom of the trough, north of the large camptonite dike,

[16] Amer. Inst. Min. Engrs., *Trans.*, XXIV., p. 121, 1894.
[17] *Loc. cit.*

the ore is massive, and thick, being 200 feet across on the 800 level, 1,020′ south.

Post-ore Fractures.—There is clear evidence that considerable fracturing has occurred in the Franklin ore-body since the deposition of the ore, these fractures in many cases cutting across the banding of the ore, and being filled with later minerals such as sphalerite, secondary willemite, pyrite, opaline silica, dolomite, and galena (Plate X., *B* and *C*).

In a few cases there is distinct evidence of movement along these breaks, but at only one place on the 130 foot level, about 400 feet north of the Palmer shaft, were any coarse breccias seen at all comparable to those at Sterling Hill. Here there is a mass of hard dense ore, more or less broken, and mixed with fragments of the Kittatinny blue limestone, while over it is the blue limestone, separated from the brecciated mass by a gouge. Just north of this the white limestone is in contact with the blue, the Hardyston quartzite being absent, while still a little farther north and below the 180 foot level there is a great brecciated mass of blue limestone and ore (Plate X., *A*). One block of ore fully 9 feet square was bounded on three sides by a brecciated mass of ore and blue limestone, the fragments being cemented by coarse calcite with some sphalerite and pyrite scattered through it.

Intrusive Masses.—The Mine Hill ore-body is cut by two classes of dikes, namely, black, fine-grained dikes, classed by Wolff as camptonites, and by pegmatites. The former are usually small, and their contact-metamorphic effect on the ore seems to have been negligible, even in the case of the largest one. In fact they are scarcely visible megascopically. Under the microscope the edge of one dike examined shows a chilled appearance, and from this there extend some very narrow stringers of a fine-grained, brownish-looking material which it was difficult to identify. These stringers in some cases cut across the willemite grains. A few tiny grains of franklinite are included in the edge of the dike.

The pegmatite, described on an earlier page, is found in many portions of the Mine Hill ore-body.

Sterling Hill.

The Sterling Hill ore-body lies near the east side of the Franklin limestone belt, not far from the major fault mapped by Spencer as separating the white limestone on the west from the Kittatinny limestone on the east.[18]

Spencer suggested that the fault plane if vertical might intersect the east limb at a depth of about 1,000 feet, but subsequent development underground has shown that such is not the case. On the 1,750 level there is a strongly sheeted zone along the east or hanging wall of the east limb, but whether this is the same displacement as that mapped on the surface cannot be definitely stated. Drill cores from a horizontal bore hole extending over 300 feet into the hanging wall of the east limb at the level above mentioned show only white limestone with patches of pegmatite,[18a] garnet and hornblende. If then the shear zone on the 1,750 level corresponds to the fault mapped on the surface, the full thickness of the Kittatinny limestone must be missing at this point.

At the time the Franklin Furnace Geologic Atlas Folio was published the limited extent of the workings did not permit accurate determination of the shape of the deposit and it was assumed from the study of the surface workings and of the upper levels that it was a simple trough, the stereogram (Fig. 13 in the Folio) so showing it. The mining work of the last few years has brought to light several new features, and while much yet remains to be disclosed by future development, some revision of previous conceptions can be made.

First, the ore-trough is far from being a smooth synclinal fold, the keel in places pitching very steeply, and in others being nearly flat. The sides of the trough are at some points somewhat buckled, possibly due to longitudinal compression, or even original irregularities of deposition. This is especially true of the west limb, where drifts which follow the ore are at times rather sinuous.

Second, the relative lengths of the two limbs in the outcrops

[18] Spencer, Loc. cit., p. 25.

[18a] Communication from Mr. R. M. Catlin.

are found to be reversed in the deeper workings. In the outcrop and in the higher levels, the east limb has a longer northward extent than the west limb; in the lower levels, on the other hand, the east limb is the shorter of the two, and the west limb extends much farther north than indicated by its outcrop.

Third, an apparent branching of the west limb has recently been encountered in the workings from the 700 foot level down. This feature has perhaps been most thoroughly explored on the 1,100 foot level. Here, what appears to be a branch of the west vein of ore starts from the west limb and cuts diagonally across the trough to a point just north of the end of the east limb, then turns northward and "carries on" in line with the latter. In its diagonal passage across the trough this east branch is extremely sinuous, and makes several sharp changes in direction. Insufficient data are at hand to state definitely whether it is a single continuous branch of the west vein or may itself send off branches.

Post-ore Fracturing.—Evidence of post-ore fracturing or faulting is quite clear in several portions of the Sterling Hill ore-body.

This may consist of, first, small closed faults, as in the 1,000 level of the west limb, second, masses of sheared rock, or third, coarse breccias. The last named consist of large angular or sub-angular pieces of ore or white limestone, surrounded by a fine-grained, usually dark-colored mass of crushed material. The matrix in which the breccia fragments are embedded is usually dark and fine-grained. Under the microscope it shows a crushed mass of ore minerals and calcite, with usually some sphalerite.

Even slipping along a single fracture may develop a thin band of crushed ore and gangue minerals, which is clearly seen under the microscope. Along some of the planes of shearing the ore minerals may be drawn out into long strings of small grains (Plates XIII., *C*, and XI., *F*). The coarse breccias in some cases may represent local crushing unaccompanied apparently by any marked displacement of the ore-body. However, there has not been sufficient development work to make any definite statements regarding this, or the other faults.

Intrusions.—At several points in the workings were observed small basic dikes, later than the ore. It was not possible to correlate these isolated occurrences, and similar rocks were not seen at the surface.

In the old open-cut workings there is a band of syenitic rock described on an earlier page. As Spencer points out, this band of rock follows quite closely the curve of the ore-body, and, as stated above, he considers that it postdates the ore.

Another interesting rock is the syenite-monzonite, already described, found in the raise between the 1,600 and 1,700 levels.

The Ores and Associated Minerals.

The principal ore minerals are essentially the same in both deposits. Named in the order of their abundance, they are franklinite, $(FeMnZn)O$, $(FeMn)_2O_3$; willemite, $ZnSiO_4$; and zincite, ZnO. Tephroite, Mn_2SiO_4, though not abundant, is widely distributed through the deposits, and should be considered with the ore minerals. The willemite and zincite commonly contain manganese and iron replacing a portion of the zinc. Hintze,[19] in fact, does not recognize willemite proper as occurring in these deposits, but considers it all to be troostite, $(Zn, Mn)_2SiO_4$. In addition to the four minerals named, minor amounts of zinc and manganese are found in other minerals, notably hardystonite ($Ca_2ZnSi_2O_7$), and leucophoenicite ($H_2(Mn, Zn, Ca)_7Si_3O_{14}$).

The ore is commonly a granular aggregate of the three minerals franklinite, willemite, and zincite, with varying amounts of calcite gangue, ranging from almost zero up to 50 per cent. The proportions of the three ore minerals also vary greatly and one or even two of them may be entirely lacking. Franklinite, however, is the only one that ever occurs in considerable amount free from the others. The gradation in composition of the ores apparently takes place in any direction through the deposits. The change may occur along a given drift in the ore, or between upper and lower levels, or between foot-wall and hanging-wall. Such changes in the character of the ore appear to be more fre-

[19] "Handbuch der Mineralogie," vol. II., p. 37.

quent and striking at Sterling Hill than at Mine Hill. In the former deposit Spencer[20] describes a rather distinct separation of the zincite from the other minerals, the rich zinc ore occurring along the foot-wall of the west limb and the hanging-wall of the east limb. At the present time a marked concentration of the zincite may be seen in a zone up to three or four feet in width along the foot-wall of the west vein, especially on the 1,000 and 1,100 levels. It extends for about 300 feet and grades into tephroite to the northwest. It is quite possible that this is the downward continuation of the zincite band mentioned by Spencer. On these lower levels, however, there seems to be no distinct separation of the zincite, but only a greater increase in its amount near the foot-wall.

According to Mr. Warren Hastings[21] of the Sterling Hill mine a striking separation of the minerals has been noted on the 1,000 foot level at the north end of the east branch of the west vein. Here the ore vein splits into three fingers, one of which consists of franklinite, another of franklinite and willemite, while the third carries chiefly hornblende. Similar occurrences are said to be found on the 700 and 1,100 levels. Hornblende is not ordinarily present in the ore.

The two ore-bodies differ in the character of the willemite which they contain. At Franklin the willemite is prevailingly green, while yellow is less common, and red or brown shades are rare. At Sterling Hill, on the other hand, the willemite is usually brown to dull brick-red in color, and the lighter shades are far less common. A second difference is in the relative abundance of black willemite[22] in the two mines. This is found only sparingly at Franklin, but at Sterling Hill it occurs in great quantities, especially in the branch of the west limb which runs diagonally across the limestone wedge between the limbs of the trough, this branch being at times composed entirely of the black willemite. This black willemite graded into a mixture of brown willemite and franklinite.

[20] *Loc. cit.*, p. 7.

[21] Oral communication.

[22] See description on page 543 of this paper.

The most important difference, however, lies in the relative amounts of silicate gangue minerals at the two localities. The paucity of these minerals, both in number and quantity, at Sterling Hill is in marked contrast with their great variety and abundance at Franklin. This is apparent from the most casual examination of the run-of-mine ore from the two deposits. Such minerals as garnet and rhodonite occur in large quantities at Franklin, but are rarely seen at Sterling Hill. Of the less common minerals, especially the rare zinc-manganese silicates, by far the larger number are thus far known only from the Mine Hill ore-body.

It seems to be commonly assumed that the zinc ores always show a banded structure, and that this is due to regional metamorphism. While such banding is not rare, nevertheless there are many parts of the ore-body where banding is not evident, while in other cases it may be more apparent than real, because of the different ore minerals with their characteristic colors, occurring in streaks, which of itself may give the ore a banded appearance.

PETROGRAPHY OF THE ORE-BODIES.

The Ore Minerals.

Introductory.—Study of thin sections affords abundant evidence that the four principal ore minerals were not all formed at the same time but that they were introduced in a definite order. The orthosilicates, willemite (excepting the secondary willemite) and tephroite, are nearly, if not quite, contemporaneous; both, however, definitely antedate the franklinite, and the latter in turn is clearly older than the zincite. The introduction of the franklinite may have started before the deposition of the two silicates was complete; between the periods of formation of the franklinite and the zincite, on the other hand, there seems to have been a complete separation.

The detailed evidence upon which the above conclusions are based will be presented in the following pages. The four minerals will be discussed separately, and the general order of their

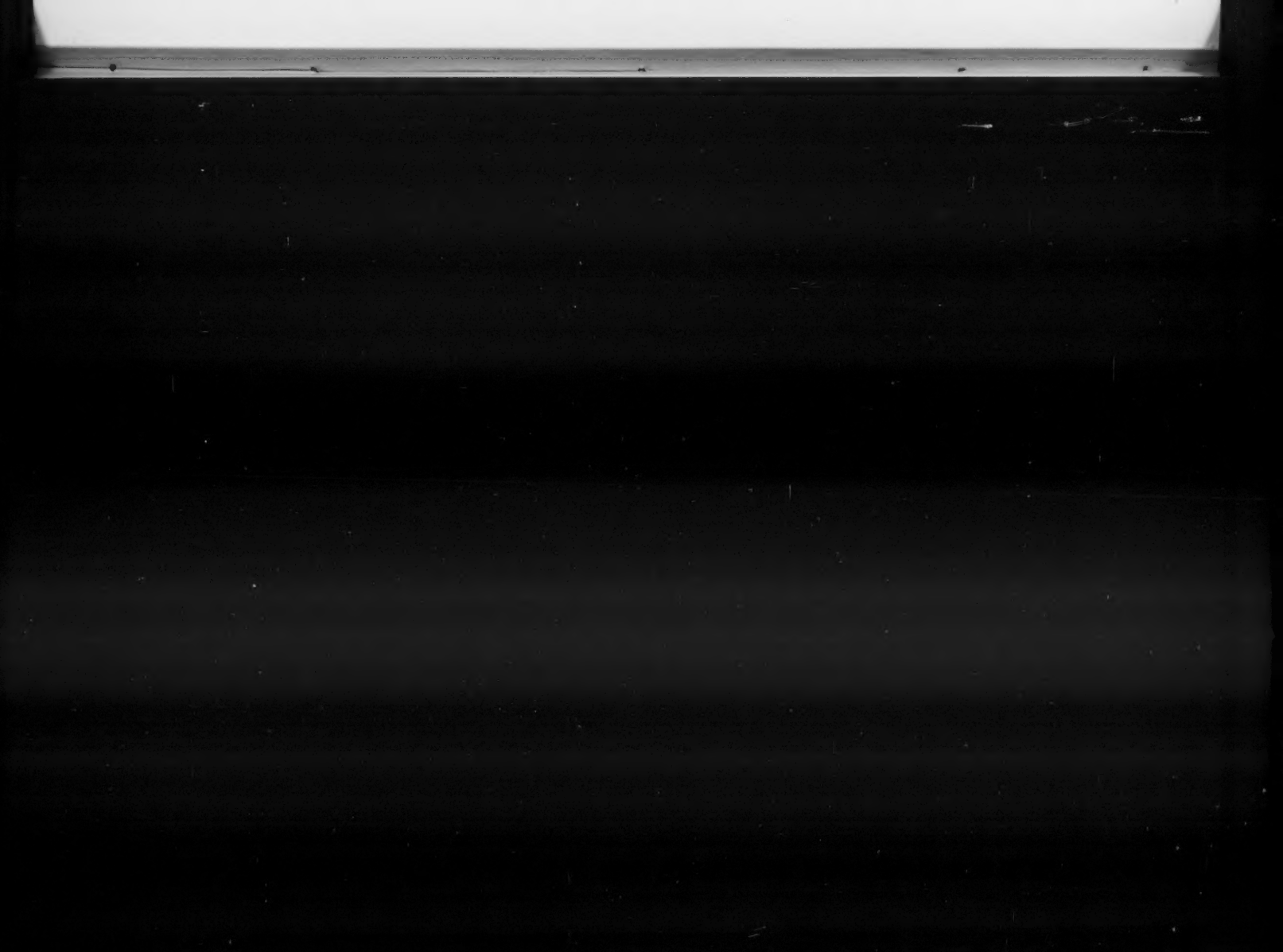
formation. The individual characteristics of the several minerals have been described in greater or less detail by many writers. However, it seems desirable to include in this discussion even familiar observations, for the reason that many of these facts shed light on the larger problem of ore genesis.

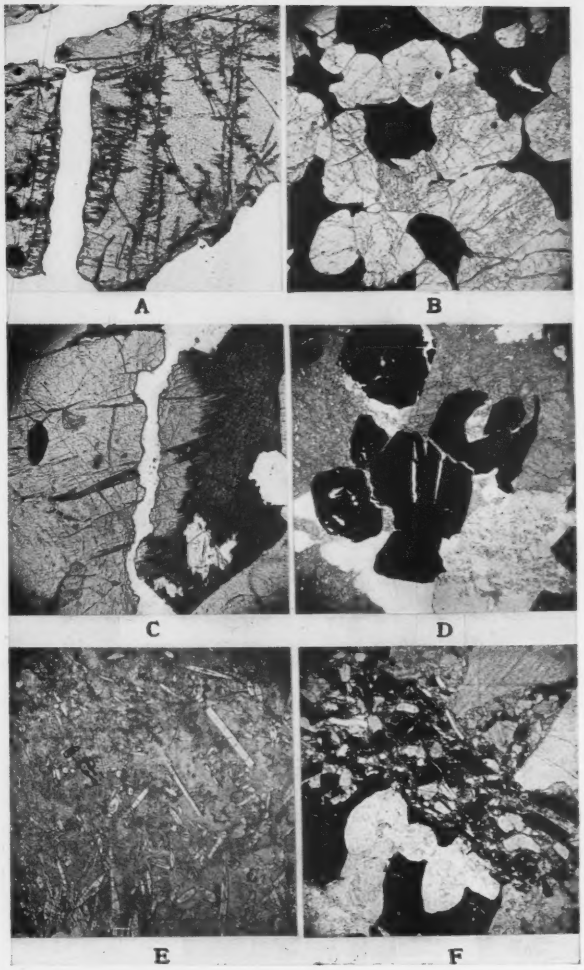
Tephroite.—Though the tephroite usually has a massive appearance in the hand specimen, in thin section it is found to be an aggregate of microscopic grains. Its optical properties agree with those given by A. N. Winchell.[23] The other ore minerals are usually associated with it. It is practically never clear, but crowded with minute inclusions, and these are frequently so numerous that the mineral is scarcely more than translucent in a section of ordinary thickness. The inclusions are sometimes concentrated in straight lines parallel to the crystal structure, and at other times distributed rather uniformly through a grain without apparent regard for the structure. They are often so small as to be unidentifiable even under high power.

Willemite.—This is of two distinct types: *I.* Compact crystalline grains, practically never euhedral, usually spheroidal or elliptical when isolated in the limestone country rock, rudely polygonal when closely crowded by other ore grains, and averaging from ⅛ to ¼ inch. *II.* Elongated crystals ranging from minute needles of microscopic size to columnar crystals which in exceptional cases are an inch or more in diameter and three or four inches in length. This second type sometimes shows excellent euhedral crystals. The first type includes the greater percentage of all the willemite in the ore-bodies, while the second type includes only an insignificant portion, consisting of material occurring in veinlets and cavity fillings. We may therefore designate the two types as "primary" and "secondary," and give them separate consideration.

Primary Willemite.—The rounded grains of this class vary greatly in megascopic appearance. Practically all colors may be observed, excepting possibly blue and violet. When colorless, yellow, or light green, the willemite is usually glassy and trans-

[23] "Elements of Optical Mineralogy."





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A. Black willemite, shows franklinite entering willemite along fractures and spreading out from same, Mine Hill, × 12.

B. Later franklinite in part replacing lighter willemite. Streaks in willemite are grains of franklinite. Normal ore, Mine Hill, × 12.

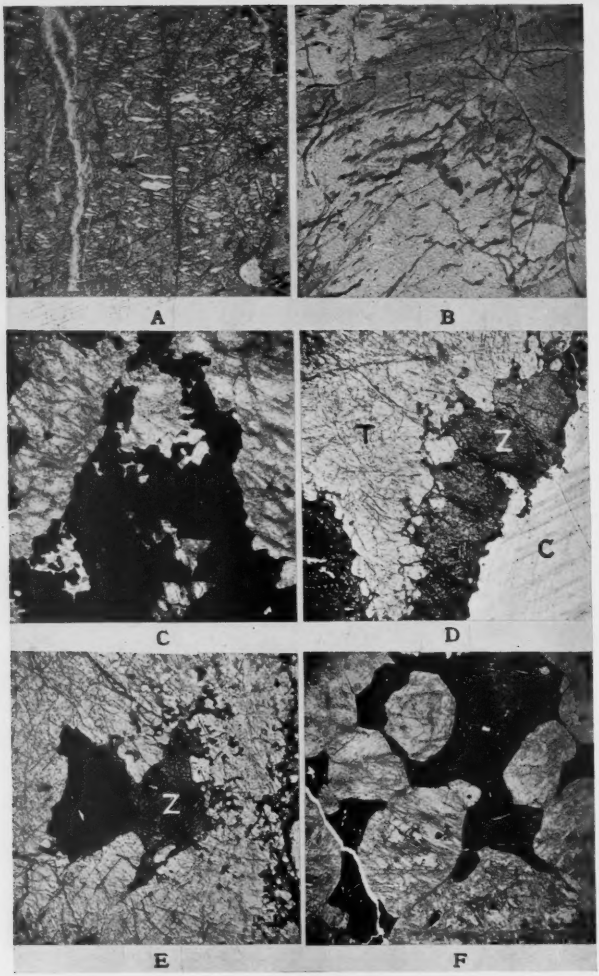
C. Zincite (dark) replacing willemite (light), Sterling Hill, × 35.

D. Zincite gray, franklinite black. Zincite can be seen entering cracks of franklinite. Sterling Hill, ×6.

E. Post-ore vein showing needles of willemite embedded in fine-grained carbonates, Mine Hill, ×12.

F. Crushed zone in ore showing broken fragments of franklinite, willemite and calcite. Normal ore on either side. Light patches in latter are willemite being replaced by calcite. Sterling Hill, ×32.

All sections photographed by ordinary light.



A. Feldspar vein cutting hornblende and replacing latter. Syenite-monzonite contact zone, 1600 level, Sterling Hill, ×32.

B. Zincite grains in red willemite, ×50.

C. Tephroite replaced by franklinite, zincite in part replacing remaining tephroite, ×36.

D. Zincite (*Z*) replacing calcite (*C*) and tephroite (*T*), ×16.

E. Tephroite replaced by franklinite (black), and later by zincite (*Z*) which cuts across tephroite in irregular veinlets and in part molded around franklinite, ×12.

F. Franklinite (black), white patches unreplaced willemite, gray calcite that has replaced willemite, ×13.

All sections photographed by ordinary light.

parent; when dark green, brown, or red, it is apt to have a duller luster, and to appear cloudy, translucent, or even semi-opaque.

Thin sections indicate that the color and transparency of the mineral are dependent upon the character and abundance of included particles; the more transparent and lighter-colored grains being relatively free from such particles, while the duller, darker grains are often crowded with them.

When the nature of these inclusions could be determined, it was found that those in the black and green varieties of willemite consisted of franklinite (Plate XI., *A, B*), while those in the brown and red varieties are zincite (Plate XII., *B*).

In sections which show both calcite and willemite, the calcite is found to be practically free from such inclusions, even though adjacent willemite grains may contain great numbers of them. Within the ore itself, the particles may be rather uniformly distributed through all the willemite grains in the section, or they may be segregated in certain grains, leaving the others clear. Within a given willemite grain the inclusions may be rather evenly distributed, or they may be gathered into bunches and knots; they may be concentrated along cleavage planes and fractures in the willemite (Plate XI., *A*), or they may be apparently independent of such structures.

Secondary Willemite.—This was observed to occur under the following conditions:

1. Lining vugs in the primary ore. Such vugs, of minute size, were noted in several thin sections. The primary willemite bordering the vugs frequently shows smooth, but uneven, surfaces which have the appearance of solution surfaces. The cavities are usually filled with opaline silica, and capillary crystals of willemite, either isolated individuals or radiating clusters, are often embedded in the silica. In one case the secondary needles had formed on the surfaces of the original willemite grains, and were growing inward toward the center of the vug.

2. Breccia-fillings. Secondary willemite is frequently found in breccias, where it forms bunches up to several inches in diameter. These bunches fill irregular spaces between the fragments

of limestone and ore, and are clearly of secondary origin. Associated with the willemite in the cavity fillings are frequently found chiefly opaline silica, calcite, and dolomite; carbonate of manganese is sometimes present.

In these occurrences the secondary crystals of willemite commonly form radiating masses. The individual crystals vary from minute needles of microscopic size to columnar individuals an inch or more in length. The finer-grained masses are frequently snow-white, while the coarser crystals are more often pale apple-green. Material of gem-quality is occasionally obtained from the latter.

3. Secondary veinlets. Narrow veinlets (seldom over an inch in thickness) (Plate X., *B*) traverse the ore-bodies in all directions. They often follow minor slips, and sometimes show close connection with breccias. They are, therefore, clearly of secondary origin. In some of these filled fractures may be found the same mineral association as that noted in the breccia-fillings, namely acicular willemite, opaline silica, and carbonates. The last named are, in many cases, so fine-grained that their specific character is uncertain. When these fine carbonate masses constitute the chief filling of the fractures, the willemite tends to occur as scattered crystals (Plate XI., *E*), commonly of spindle-shaped form. In other instances the minerals form separate bands in the veinlet. A specimen loaned by Professor F. B. Peck of Lafayette College shows silica coating the walls of a fissure, with the willemite filling the remainder.

4. Filling minute fractures in franklinite. In thin sections the franklinite grains are very commonly found to be fractured, and in these fractures occur several different minerals, not all in the same fracture. Among these, needles of willemite have been observed. As stated previously, the primary willemite antedates the franklinite, consequently the acicular material in the cracks of the franklinite is obviously of later origin.

Fluorescence of Willemite.—A number of specimens of willemite were exposed to the ultra-violet light, and it was noticed that while both primary and secondary willemite were fluorescent, the

secondary willemite was also phosphorescent. One specimen of red primary willemite, full of zincite inclusions, showed no fluorescence.

Alteration of Primary Willemite.—Though no considerable alteration of willemite was observed in the thin sections some evidence was noted, as follows:

1. Solution and redeposition. In the preceding discussion of secondary willemite, reference was made to the apparent solution of primary willemite adjacent to vugs, and its redeposition in acicular form, together with silica and other minerals. There is no direct evidence as to the nature of the solutions which might have accomplished this transfer. However, it seems probable that hot circulating waters accompanying post-ore intrusions of pegmatite dissolved portions of the ore and later deposited this material in the form of new minerals. It is not improbable, therefore, that in the case of the vugs described, such waters affected both solution and deposition. In fact, it seems quite probable that the secondary willemite, in most or all of its occurrences, owes its origin to this process, and therefore may date from the time of the pegmatite intrusions.

2. Alteration to silica and carbonates. Evidence of this type of alteration is furnished by a single section cut from a specimen of lean ore from the dump. In this section many of the willemite grains contain areas which consist of a network of minute veinlets of opaline silica, the spaces between which are filled with extremely fine-grained crystalline material—evidently carbonates (Plate XIII., *A*). These areas are most common around the margins of the grains, especially where calcite adjoins the willemite. From the margins the alteration has worked inward, for the unaffected central portions of the grains have corroded outlines. The altered areas often occur as deep embayments in the willemite, and occasionally they have the form of lath-shaped tongues penetrating the willemite along the cleavage planes. Sometimes several remnants of willemite in an altered area extinguish simultaneously under crossed nicols, proving their identity as parts of one original grain. It is not by any means certain whether this

represents a dissociation of the willemite, or its replacement by foreign material.

3. Replacement of willemite by calcite. In a breccia on the 1,400 level of the west limb, at Sterling Hill, angular fragments of limestone are embedded in finely-granulated ore. Microscopic examination of the crushed material disclosed practically no willemite, though the undisturbed ore nearby was a rich willemite-franklinite mixture. A thin section cut across the contact between the breccia and the unbroken ore likewise showed no willemite in the ore immediately adjacent to the breccia, instead, rounded areas between the franklinite grains contained only fine-grained calcite. At distances of ¼ to ½ inch from the breccia, however, small corroded particles of willemite were found, and often several of these pieces were grouped near the center of a rounded area of calcite (Plate XI., *F*). Furthermore, it is significant that within any one such area, all the fragments of willemite possessed the same crystallographic orientation. The general relationships of the calcite, willemite, and franklinite leave little room for doubt that the rounded areas of fine-grained calcite were originally occupied by willemite grains, and that the corroded particles of willemite within a given area are unreplaced remnants of a single original grain. It is evident that solutions circulating through the breccia have replaced the fragments of willemite by calcite, this accounting for the absence of willemite there; further, these solutions have permeated the undisturbed ore adjacent to the crushed zone and have effected replacement of portions of the original rounded grains of willemite.

Willemite-Tephroite Relationships.—In the very few sections where the two silicates were found in association they occurred as granular intergrowths which indicated contemporaneous formation, though it is possible that the tephroite slightly antedated the willemite.

An interesting case of simultaneous alteration of the two minerals was found in one section in which they occur closely intergrown. The alteration resulted in a plumose mineral which penetrates both tephroite and willemite, though showing some

preference for the latter. This plumose material proved to be biaxial, and positive, with a rather small optical angle. From these characters, and from its relations to the two original minerals, it seems probable that it is a member of the isomorphous series of Zn-Mn orthosilicates.

Franklinite.—This mineral may occur in a granular mixture with the other ore minerals, or at other times may form solid masses by itself. In thin section the grains are rounded, polygonal, or very irregular in shape, depending upon the degree of crowding by adjacent ore grains. Euhedral crystals are seldom found.

Various mineralogists have noted the fact that franklinite is frequently translucent in thin chips, and that it then exhibits a blood-red color by transmitted light, but this property varies greatly in different specimens. At one extreme are rare examples which have a decidedly glassy luster, and even in hand specimens show the deep red color where internal reflections occur;[24] at the other extreme are specimens which are opaque even when crushed to particles of microscopic size. The same gradation may be observed in thin sections, for in some the grains glow deep red over their entire area, while in others they are translucent only on thin edges, and in still others it is almost impossible to find any translucent particles.

To test the degree of correspondence between the translucency of the franklinite and the thickness of the section, a series were selected, showing varying intensity of color, and their thicknesses carefully determined. It was found that there was no definite correlation between color and thickness; in fact, the section which showed the strongest color chanced to be, also, the thickest one of the series, being .033 mm.

A sample of the franklinite which yielded the strongest red color of the above series was analyzed in the laboratory of the New Jersey Zinc Company at Franklin, with the following result:

[24] A splendid crystal of this type is in the collection of Mr. Canfield, of Dover, N. J.

Fe_2O_3	57.39	CaO	2.52
FeO	1.24	MgO	.70
Mn_2O_3	0.039	SiO_2	2.44
MnO	7.24		99.259
ZnO	22.48		

Many of the larger crystals of franklinite are much fractured, and sometimes apparently sheared along nearly parallel planes. The smaller grains—those in the ordinary granular ore—seldom show this to the unaided eye, but appear compact and solid. In thin section, however, the majority of these smaller individuals are likewise found to be broken. The shattered franklinite is not confined to crush-zones (Plate XI., *F*), but is found in all parts of the ore-bodies; and when associated with willemite, the latter mineral rarely shows any signs of fracturing, but is entirely solid and unbroken.

The cracks in the franklinite contain a variety of different minerals, including often calcite, garnet, sphalerite, zincite, and willemite (secondary needles), three or four of them occurring in the same franklinite grain, but not all in the same crack. The manner of occurrence of these minerals indicates clearly that they were not involved with the franklinite in the brecciation, but were deposited after the fractures were opened.

Franklinite-Willemite Relationships.—1. Evidence from intergrowths. In thin sections which show the two minerals in granular intergrowths, the willemite grains tend to maintain rounded outlines, while the franklinite fills the irregular spaces left (Plate XI., *B*). The typical outline of a franklinite grain is thus an alternation of rounded concavities occupied by willemite, and pointed tongues which project between the grains of the latter mineral. Frequently two or more franklinite grains are entirely connected by these slender tongues, and the mass then appears as a network of franklinite with the "meshes" filled by rounded grains of willemite. In other cases, where these tongues do not effect a complete junction, a streak composed of fine particles of franklinite extends across the gap; such dust trails usually pass between willemite grains, but at times they pass directly through the willemite.

With low magnifications the curving boundaries between the two minerals usually appear smooth. With higher powers, however, it is frequently found that the surface of the franklinite bears numerous minute tongues, or spurs, which project into the willemite. Occasionally such tongues become prominent, and penetrate deeply into the willemite grain.

2. Evidence from inclusions. The occurrence of franklinite as inclusions in willemite was alluded to under primary willemite. In size these range from inclusions of megascopic size with a diameter ⅓ or ½ that of the enclosing willemite grain, down to granules so small that even when magnified 1,000 or more diameters they appear as minute dust-like particles. The smaller grains may (*a*) form trails which lead from the larger inclusions; or (b) they may be collected in definite lines which follow fractures or cleavage planes of the willemite, or (*c*) they are often distributed throughout the willemite without apparent regard for its crystal structure.

Plate XI., *B* shows the manner of occurrence of these inclusions in a granular mixture of the two minerals. The most striking examples, however, are afforded by the so-called "black willemite." In its purest form this is merely a glassy willemite so thoroughly charged with microscopic particles of franklinite that the whole mass is colored black. Plate XI., *A*, showing such an occurrence, in which the concentration of the franklinite has taken place along curved fractures, from which it has penetrated for short distances along the cleavage planes, is especially marked. With increasing size of the inclusions we find many small grains of franklinite surrounding the willemite and penetrating it, the tongues often connecting with the lines of inclusions. With still further increase in size, the ore loses its glassy appearance, and finally passes into a granular aggregate of the two minerals, as shown by Plate XI., *B*.

Such relationships as those described in the above paragraphs seem conclusive evidence that the franklinite was introduced after the willemite, and has replaced portions of the latter.

Franklinite-Tephroite.—In thin sections the franklinite is commonly found sending ragged tongues into the tephroite (Plate XII., *E*). Close examination of these tongues shows that their margins are highly serrate, minute projections passing laterally into the tephroite mass. The latter is found to be very finely granular, and the small projections of the franklinite are found to be cutting between the individual tephroite grains.

Zincite.—In thin sections the zincite appears as irregular granules and granular masses, seldom or never showing crystal outlines. In thinly-ground sections it has an amber-yellow color, in thicker ones it is dark reddish brown. Several specimens in the authors' collection show veinlets of zincite, from ¼ inch to 1 inch in width, apparently cutting across the banding of the franklinite-silicate ore. This would indicate that the zincite was the latest of the ore-minerals to be introduced, and this conclusion seems supported by the following evidences from the thin sections.

Zincite-Willemite Relationships.—1. Intergrowths. The zincite is repeatedly found working around and between grains of willemite in a manner quite comparable to the way in which franklinite tends to follow the boundaries between willemite grains. Slender stringers of zincite frequently cut through willemite masses, often branching and reuniting around individual grains of the willemite. When willemite and calcite adjoin each other, the zincite commonly follows their contacts, working into and replacing both.

2. Replacement. The zincite is frequently found replacing willemite in an irregular fashion, leaving roughened boundaries between the two minerals. Sections cut from a sample of rich ore from Sterling Hill showed the clearest case of replacement encountered. The zincite sends long splinter-like tongues into the willemite (Plate XI., *C*), these tongues always being parallel, or nearly parallel, to the cleavage of the latter mineral. Equally striking are minute needle-like growths of zincite penetrating the willemite. These are best developed where the zincite forms narrow tongues between willemite grains; in such cases the whole

of the zincite stringer is sometimes made up of transverse needles which penetrate the willemite on either side, always parallel to the cleavage of the willemite. These are often so closely spaced that the willemite is likewise reduced to the form of slender needles, so that the study of a small area along such a contact might not indicate which mineral was being replaced. The larger relations leave no room for doubt that the zincite is the replacing mineral, and postdates the willemite.

3. Inclusions. Sections of red willemite commonly show inclusions of zincite (Plate XII., *B*). When these can be resolved into definite forms by high magnification, it is found that they are thin, flat bodies, unlike the rounded inclusions of franklinite, and that they lie in the cleavage planes of the willemite. They are often lath-shaped or quadrangular; in a section from a very red specimen they were prevailingly dendritic in shape, some of them exhibiting highly branching forms. It seems that the zincite has spread into willemite in the same manner as franklinite.

Zincite-Tephroite Relationships.—The zincite sends irregular, serrate tongues into the tephroite, exactly in the manner followed by the franklinite. Smaller "spurs" on the sides of these tongues project between the small individual granules of the tephroite mass. This is well shown in Plate XII., *C, D, E.* It is clear that the zincite is the later mineral.

Zincite-Franklinite Relationships.—No definite evidence was observed to indicate that the zincite ever actually replaced the franklinite. In granular ore-mixtures the zincite was very definitely replacing willemite and tephroite, but the franklinite was left unaltered, frequently remaining as isolated grains embedded in zincite after the silicates had been completely replaced by the latter. Two direct lines of evidence do, however, indicate that the zincite postdates the franklinite.

1. The zincite shows a strong tendency to follow the boundaries between franklinite and other minerals, as willemite, tephroite, and calcite. Slender stringers cutting the silicate ore are frequently deflected by grains of franklinite, and following the borders of the latter, work out into the adjacent silicates or cal-

cite. Plate XII., *E*, shows such an occurrence in which the zincite has moulded itself around the franklinite grain, and narrow stringers have followed the boundary of the grain for two thirds of its circumference.

2. The zincite is repeatedly observed in fractures in the franklinite (Plate XI., *D*). It occurs both as scattered particles of zincite, along with secondary willemite and other minerals, these together making up the fracture-filling, and as tongues leading into the fracture from an adjacent zincite mass. In either type of occurrence, the zincite was certainly formed after the opening of the fracture, and did not come into such positions by being involved in the brecciation of the franklinite.

Resumé of Ore Relations.

A definite paragenesis of the ore minerals is indicated, beginning with the tephroite and willemite, passing then to the franklinite, and ending with the zincite. The two silicates were introduced contemporaneously, or nearly so, and were deposited as more or less thickly disseminated grains replacing the limestone. Following this stage of ore-deposition, and possibly overlapping it slightly, came the introduction of the franklinite. This was deposited in part as scattered grains in the limestone, in part by replacement of the silicates, but chiefly by replacement of the calcite remaining between the earlier silicate grains. At a still later stage the zincite was brought in, and this likewise replaced both the limestone and the silicates, and entered fractures in the franklinite.

The above paragenesis indicates a progressive change from relatively acid solutions depositing the orthosilicates to very basic solutions depositing the oxide. Such a progressive change in composition suggests, in turn, that the ore-bearing solutions were of magmatic origin. Taking into account the chemical nature of the ore-minerals, it is difficult to conceive of their having been deposited from cold solutions. These considerations lead to the conclusion that the ore-bodies are high-temperature metasomatic replacement deposits.

Non-Metallic Minerals Associated with the Ore Minerals.

A large number of non-metallic minerals have been found more or less closely associated with the ore minerals, some of them being in actual contact with them. A few of these may occur in considerable abundance, especially at Franklin, while others are exceedingly rare. Indeed not many of them were found during the writers' visits to the mines. Since these non-metallic minerals are of interest and importance because of their possible relation to the ore, some attention was given to those of which it was possible to obtain material for study.

It is quite conceivable that these non-metallics found associated with the ore might have been derived from at least four possible sources. They might represent: first, minerals such as are found in the Franklin limestone in this region, and whose exact source is open to doubt; second, minerals deposited in the limestone at the same time as the ore-minerals; third, minerals introduced into the ore-bodies at the time of the pegmatite intrusions, and derived from them, or formed as the result of the pegmatite juices reacting with the zinc-ore minerals; or, fourth, minerals deposited in post-ore fractures, and probably subsequent to the pegmatite injections.

So far as the writers' observations go, none of the non-metallic minerals considered here fall in the second group, and in a few cases it may be difficult to decide whether a mineral belongs in group 1 or 3.

Spencer gives some space to a discussion of the origin of the non-metallic minerals[25] and says that "It is believed that the metal-bearing silicates were formed by an interchange of materials between the previously existing ore-body and the invading pegmatite."

If this hypothesis is correct, the zinc-bearing silicate gangue minerals at least must definitely postdate the ore.

The non-metallic minerals which were observed in thin sections of specimens taken from the ore-bodies are described below, the important ones being referred to first.

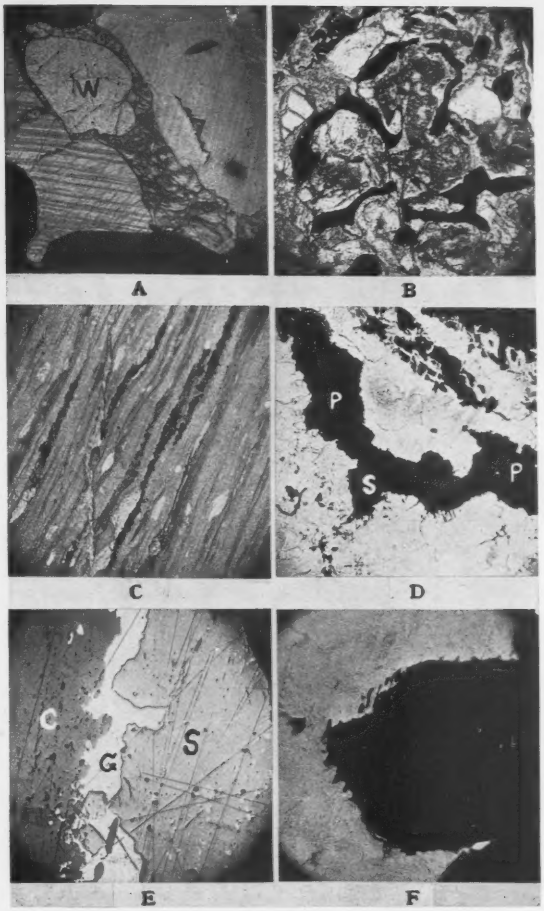
[25] *Loc cit.*, p. 8.

Silicates Associated with the Ore.

Garnet.—This mineral was observed in a number of specimens collected at Mine Hill. No specimens were obtained at Sterling Hill, except in the syenite contact zone in the old Calamine pit. The mineral occurs occasionally in isolated grains replacing the white limestone, and at other times in contact with the ore-minerals. It sometimes occurs in the ore-body in solid masses bordering the pegmatite. Where it was observed in contact with willemite, the latter was usually much corroded and altered, actual replacement by the garnet being common, and corroded remnants of willemite were frequently noticed within garnet masses.

In sections showing both willemite and franklinite, there was sometimes apparently complete replacement of the willemite, while the franklinite grains remained unattacked, but surrounded by garnet. If the franklinite was fractured, as is usually the case, these cracks were found partially or wholly occupied by garnet. In a few slides, however, the surrounded franklinite grains, instead of preserving their usual rounded form, showed curious serpentine shapes (Plate XIII., *B*), this being most pronounced in the case of grains which were well within a garnet mass, while toward the border of such a mass the effect was less marked and outside of the garnet zone the franklinite was entirely normal. These serpentine shapes appear to have resulted from the irregular corrosion of the franklinite by the garnet. Analyses of the garnet are not available, but according to Palache many specimens tested show manganese, which might have been obtained from the franklinite.

Rhodonite.—This is not a rare mineral in Mine Hill. Specimens collected ranged from pieces 4 to 5 inches across to minute grains occurring in the ore. Like the garnet, the rhodonite may show selective replacement of the willemite, leaving the franklinite unaffected. It may be found, too, entering fractures in the latter. Hand specimens occasionally show an interbanding of franklinite and rhodonite in which the two minerals have every appearance of being contemporaneous in origin. Sections



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A. Willemite (*W*) altering to a mixture of silica and carbonates, Sterling Hill, ×24.

B. Franklinite (black) surrounded by garnet and corroded by same, Mine Hill, ×23.

C. Sheared band showing grains of franklinite (black) drawn out into narrow streaks, and embedded in finely granulated carbonate of lime, Sterling Hill, ×15.

D. Limestone showing post-ore veinlet of sphalerite, the latter in part replacing calcite. Black center of vein later pyrite. Upper right, black angular grains of franklinite due to fracturing of ore, Mine Hill, ×12.

E. Polished surface showing vein of galena (*G*) cutting through and in part replacing sphalerite (*S*) and calcite (*C*). Light spots in sphalerite are later chalcopyrite, ×30. Mine Hill.

F. Grain of magnetite in feldspar. Shows resorption of magnetite. Pegmatite, Mine Hill, ×80.

A–D, and *F*, thin sections, ordinary light.

cut from specimens of this character showed badly corroded remnants of willemite in the rhodonite. The latter evidently postdated the ore, but by replacing the willemite grains and assuming their shape and position, had simulated contemporaneity with the franklinite.

The rhodonite proved to have a variable optical behavior. Some sections display the usual optical properties of rhodonite, such as low birefringence, negative sign, small optical angle, and dispersion $\rho < v$. Others exhibit much higher birefringence, positive sign, optical angle close to 90°, and dispersion $\rho > v$. The chemical reason for this variation was not investigated and there is a possibility that some so-called rhodonite is a monoclinic pyroxene.

Hardystonite.—This mineral has been found only at Franklin and chiefly in the northern half of the ore-body. It occurs in massive form, usually associated with franklinite and willemite. All of the material containing hardystonite was obtained from the picking table, and therefore its occurrence was not observed. One hand specimen of particular interest showed the normal franklinite-willemite mixture, in contact with which is a band of garnet, following which is a zone of biotite and caswellite; finally, the rest of the specimen is massive hardystonite. It might be assumed that the successive mineral bands were all formed in a contact zone adjacent to a pegmatite intrusive, but this is incapable of proof.

In thin sections the almost universal presence of narrow contact rims between hardystonite and franklinite is noteworthy. The nature of the material in these rims could not be determined positively, though some portions of them seemed to be composed of leucophenicite (H_2(Mn, Zn, Ca), Si_3O_{14}). The material of these rims may be seen working into the franklinite along fractures. Small grains of franklinite were found, with this material following fractures entirely across the grain, joining at each end with the surrounding rim. Such relations seem to indicate clearly that the hardystonite, like the garnet and rhodonite, was introduced not only later than the franklinite, but even later than the fracturing of the latter.

In hand specimens the hardystonite frequently shows a slight yellowish color. While this may occasionally be merely an external discoloration, thin sections indicate that it is sometimes due to the presence of fine granules of zincite sprinkled through the massive hardystonite. These particles are always in, or closely associated with, small altered patches in the hardystonite. This suggests that the zincite may be a product of alteration of the latter; such a theory gains weight from the fact that the zincite is most abundant near franklinite borders, as though the chemical changes which produced the contact rims reacted on the hardystonite with the separation of zincite. Or, may it be that the zincite is the result of simple dissociation of the hardystonite? If we can assume such dissociation occurring at all, it is conceivable that the hardystonite, $Ca_2ZnSi_2O_7$, might break down into ZnO, zincite, $+ 2CaSiO_3$, wollastonite. In those sections where alteration products had formed they were too fine grained to be determinable.

While the hardystonite theoretically is a lime-zinc silicate, it nevertheless may sometimes show lead both on chemical analysis and spectroscopic examination. None of the thin sections, even when examined with high power, showed any grains of galena, and the inference is that some of the zinc may be replaced by lead.

Other Non-metallics.—Biotite occurs as a contact mineral of the acid pegmatite and in the rocks previously described. Some of that seen in the ore may belong to the limestone metamorphism which preceded the ore. Calcite and dolomite have been noted in post-ore fractures. Chlorite was observed as an alteration product. It also occurs filling cracks in magnetite, and in ore from Sterling Hill as veinlets cutting across franklinite and even willemite. Chondrodite was not noted in the ore except in the case of the magnetite ore at Mine Hill. Epidote occurs in the pegmatite at Mine Hill and its contact zones at Sterling Hill. Sphene and spinel were also noted in the pegmatite at the former locality. Feldspar and tourmaline have already been noted in the description of the rocks. Fluorite is found not only in the limestone quarries but also as a later mineral in cavities in the ore.

Leucophœnicite was identified as forming what appeared to be reaction rims between hardystonite and franklinite. We are informed by Dr. E. T. Wherry that much of the material from Mine Hill which has been identified as leucophœnicite is really pyroxene. Pyroxene was rather scarce in the ore sections examined by the writers. Some specimens which megascopically were called rhodonite proved under the microscope to be monoclinic pyroxene. Where associated with zinc ore, it is usually later than the ore minerals. Tourmaline was noted in the "eyes" of the gray gneiss at Mine Hill.

Minor Metallic Minerals.

Sulphides, sulpho-salts, oxides and native metals in considerable variety have been found with the ore-bodies, but are never in sufficient amounts to have any economic significance, indeed, they usually occur in isolated streaks in pockets.

Most of these are very rare, and did not come under the authors observation. Only those of which they have personal knowledge will be mentioned here.

Sphalerite.—This mineral, though not common, shows at least four types of occurrence as follows: 1. In pegmatite masses. This association was not observed by the present writers, but is reported by Palache.[26]

2. In direct association with the ore. It is sometimes observable as secondary veinlets cutting the ore (Plate XIII., *D*), and also as irregular masses. In thin section it was seen in small amounts moulding itself around ore grains, and running into cracks in franklinite. In a section cut from a veinlet of secondary willemite, likewise, the sphalerite was found filling interstices between the willemite needles, and frequently moulded around them. Transverse fractures in some of these needles from a Mine Hill specimen were filled by the sphalerite.

3. In post-ore breccias. At several points in the ore-bodies are found breccias which include the ore, and in which sphalerite forms specks and bunches in the secondary calcite fillings. In

[26] U. S. Geol. Atlas Folio, 161, p. 9, 1908.

one such occurrence, in the north end of the Franklin workings, the crushing has involved the overlying sedimentary beds, and large fragments of the Kittatinny limestone are included in the breccia. In this case, too, sphalerite is present in the calcite filling, in bunches up to an inch or more in diameter (Plate X., *A*).

4. In post-ore fractures. In these the sphalerite may be the only mineral, or more frequently it is asosciated with dolomite and calcite. Occasionally it is found in the same fracture as secondary willemite, but is evidently of later age.

5. In isolated pockets in the limestone. Occasional pockets several feet in diameter, containing a mixture of sphalerite, pyrite, galena, and chalcopyrite, are found in the Franklin limestone near the ore-body at Franklin. Study of polished specimens revealed a very clear paragenesis, the minerals being introduced in the order just given. The sphalerite varies in texture from fine to coarse grained, and may be deposited either in open cavities, in the cracks of preëxisting ore minerals, or by replacement of limestone.

Judging from its relations as we saw it, the sphalerite is in every case associated with post-ore fracturing, and it is found under these conditions both at Mine Hill and Sterling Hill.

Some question may be raised as to the age of the sphalerite. There is no doubt that it was introduced later than the ore, and Spencer has suggested that it came from the pegmatite, a view that might possibly be borne out by Palache's recording its occurrence in the pegmatite. It seems to the writers, however, that most of it must be later, and not contemporaneous with the pegmatite intrusion. Indeed, some of it is undoubtedly of post-Ordovician age. The occurrences at Sterling Hill, for example, are not near pegmatite.

Pyrite.—This is to be found in every one of the types of occurrence described above for sphalerite, but in addition it occurs in greatest quantity in contact rims bordering the pegmatite intrusions. Such rims are sometimes made up wholly of pyrite, with a width up to two feet or more.

In the breccia in the Franklin mine, noted above, the fragments of Kittatinny limestone were seen to be partially coated with pyrite. It is interesting that this coating is well developed on only one side of each fragment, and all of them are coated on the same side. The position of these coated faces in the rock is not known, as the specimen was collected from fallen material in the stope and the presence of pyrite was not noticed until the specimens were polished and studied in the laboratory.

The relative age of the sphalerite and pyrite cannot always be determined. However, in all cases studied in which the two minerals were so closely associated as to permit such determination, the pyrite was found to be the later. Plate XIII., *D* shows a veinlet with sphalerite on the walls and pyrite in the center, clearly indicating the later age of the latter.

Since some of the pyrite occurs in the contact-metamorphic zones of the pegmatite and some in post-Ordovician fault breccias, it would indicate at least two periods of deposition of this mineral.

Galena.—This sulphide never occurs in large quantities, although it has been found in small amounts at a number of points in the limestone near the ore-bodies.

It is difficult to obtain accurate data regarding the occurrence of galena at Mine Hill, but during the summer of 1921 a considerable pocket of galena, sphalerite, and chalcopyrite was struck between the ore and hanging wall of the west limb on the 300 level. From the specimens there collected the galena appeared to be later than the sphalerite, cutting through it sometimes in well-defined veins or sending tongues into it (Plate XIII., *E*).

Several specimens which we have from Mine Hill show galena grains apparently embedded in garnet. As these were obtained from the picking table their exact source could not be ascertained. If the material is contemporaneous with the garnet, it would indicate that it is a contact product of the pegmatite, and such an inference would be in accord with Palache's views regarding an occurrence reported by him. The thin section of our material shows clearly that the galena is replacing the garnet.

At Sterling Hill, according to Mr. Warren Hastings, no galena

is found within the ore, but it is noticed in the basin between the ore-bodies in association with sphalerite, and also in the 1,400 level in a crushed zone in the footwall of the west limb.

Another specimen which we have shows a vein of galena cutting across the ore. Close to it there is a band of opaline silica.

Reference has also been made to its occurrence in the contact zone of the syenite in the wall of the old calamine pit.

Chalcopyrite.—The only occurrence of chalcopyrite seen by the writers is that noted above under Galena. Palache observes that its occurrence is rare at both Mine Hill and Sterling Hill.

The specimens from Mine Hill contain sphalerite, pyrite and galena. When polished and studied under the microscope they showed chalcopyrite veinlets cutting across all three of the above-mentioned sulphides, and as strings of inclusions in the sphalerite.[27] It therefore seems to be of later age than any of them.

Chalcocite.—None of this mineral was seen in place by the writers, but several specimens came into their possession, and they also had the opportunity of seeing several others in private collections. Judging from all these the material appears to fill secondary fractures in the ore. It is not mentioned in the list of minerals given in the Franklin Furnace Geologic Atlas Folio. One specimen seen, which came from the 812 section, 990 level, showed the chalcocite cutting across the banding of the ore. Another specimen associated with magnetite was obtained from the 1,050 level, 401 south, Mine Hill. Mr. R. M. Catlin informed us that some was found in the 1,000 level, 401 section, associated with native silver.

Native Copper.—While this is not abundant it has been found from time to time, and its introduction evidently postdates the zinc ores, for many of the specimens not only show evidence of deposition in fractures, but some of the latter cut across the banding of the ore. In none of the specimens seen did the ore show any signs of weathering, so that the copper was probably a primary mineral. It occurs chiefly in thin flakes and sheets,

[27] In this connection see L. P. Teas, "The Relation of Sphalerite to other Sulphides in Ores," Amer. Inst. Min. Engrs., *Trans.*, LIX., p. 68, 1918.

some of the latter a foot across. What its relation to the chalcocite is we are unable to say, as no specimens of the two in contact were seen. From the few data that we were able to obtain the material has been found on the 450 level, 564 north, Mine Hill. It has also been found in the 360 and 500 sections north, at the same locality.

Of some interest is an occurrence of native copper associated with cyprine, found in the Mine Hill workings during the summer of 1920. The specimens show a fine-grained mixture of cyprine (blue vesuvianite) and garnet, both replacing calcite. Some of the cyprine occurs as long narrow crystals. The native copper occurs as small grains, visible, however, to the naked eye, and being found in both the cyprine and calcite. Its associations are of interest as indicating that it was formed under high-temperature conditions, and because of its close association with the two silicates above mentioned may be a product of the pegmatite intrusions.

Another interesting occurrence is that of copper observed in specimens from a limestone quarry three miles north of Franklin. These were taken from a contact phase of the limestone, and a conspicuous mineral in most of them is apatite. Small sheets of copper are wrapped closely about some of the apatite crystals, while other sheets are embedded in apatite. In view of such relationships, the copper here seems to be a contact-metamorphic mineral, hence at this locality also of high-temperature origin.

Spencer,[28] in a classification of post-ore minerals, places native copper among the products of pneumatolytic action.

Magnetite.—The chief occurrence of this is in the gray and pink pegmatite at Mine Hill and in the magnetite deposit associated with the west limb of the ore-body. A little is reported from the zinc ore-bodies. Some of the magnetite shows replacement by hematite.

Hematite.—This was noticed chiefly as an alteration product of franklinite, occurring either as microscopic acicular crystals on the surface of the same, or as radiating needles in the calcite

[28] *Loc. cit.*, p. 10.

adjoining it. One specimen from an unknown location in Mine Hill showed the hematite replacing both magnetite and garnet.

ORIGIN OF THE ZINC ORES.

The origin of the zinc-ore deposits in Mine Hill and Sterling Hill has long been a puzzling problem to geologists and various opinions have been expressed regarding them. It is perhaps easy to understand why this is so; firstly, they occur in metamorphic rocks and there has been a feeling of uncertainty as to how much metamorphism has obscured the original relations of the minerals. Secondly, as the mines were developed more and more, new structural features were uncovered which threw additional light on the problem, and thirdly, little seems to have been done in studying the ores petrographically. This last point was an important consideration in leading the writers to undertake the present investigation.

Kemp[29] writing on these ores some thirty years ago, before much development had taken place, expressed the opinion that the ores were most probably deposited from solutions set in circulation by the intrusive rocks. These solutions spread through a particular bed, or along a particular set of bedding planes in each locality, replacing and impregnating the walls with ore. He believes that the kind of minerals which were first deposited is doubtful, but suggests that one might expect sulphides, although no trace of them is found. The present character of the ore is supposed to be largely the result of metamorphism.

Folding of ore and wall rock occurred subsequently, and was followed at a still later date by the intrusion of the large basic dike at the Buckwheat mine in Mine Hill.

Spencer[30] believes that the two deposits at Mine Hill and Sterling Hill may be assumed to have originated in the same way, and that the latter shows features which indicate that the materials of the ore could not have been deposited by sedimentation contemporaneously with the limestone, but were introduced after

[29] N. Y. Acad. Sci., *Trans.*, XIII., p. 92, 1893.
[30] N. J. Geol. Surv., Ann. Report, 1908, p. 50.

considerable deformation took place. This view he thinks is borne out by the occurrence at Sterling Hill of the great mass of lean ore between the limbs of the trough. The layer of massive ore could, in his opinion, have received its present shape by simply folding if it had originally been an intercalated bed in limestone, or a definite stratum replaced by ore, but the great mass of lean ore can only be explained by segregation after the (local) structure had been produced. The local folding is regarded as a mere incident in the general deformation and "not as marking in any way the end of metamorphism assignable to the period of igneous injection and deep-seated flow." On account of the general similarity between lean ore and richer material of the definite layer in the limbs, it is assumed that they are closely related in origin, and that the whole deposit was formed "out of invading materials." The lean ore, Spencer believes, was probably deposited by solutions which permeated and partly replaced the limestone. The richer ore occurring in the massive layer, he thinks, may have been formed in the same way, "but this is not capable of definite proof and it may be that the main ore layer at Sterling Hill and the mass of ore at Mine Hill were injected bodily into the limestone after the manner of igneous rocks." If this were true the lean ore might have been deposited by solutions accompanying the igneous injection.

The masses of pegmatite were intruded into the ore-body at Mine Hill after the folding, and most of the uncommon minerals of this locality are supposed to have been formed under the metamorphosing influence of this intrusive. This is borne out by the fact that these minerals occur along the pegmatite contacts.

Several other observers have referred to some of the geologic relationships at Franklin. Thus Wolff[31] noted that in the 950 level of the Parker shaft, the granite (pegmatite) dikes could be seen cutting the ore, sometimes parallel, at others transverse, to the banding of the ore. He states that the granite was finer grained at the contact, and that there was a contact zone of gar-

[31] *Science*, N. S., VIII., p. 560, 1898.

net and indurated ore, tending to show the intrusion of the granite into the preëxisting ore-body.

Kümmel in referring to the chemical composition of the white crystalline limestones[32] remarks that in the Parker shaft the limestone on the surface and to a considerable depth is low in magnesia, both near and remote from the ore.

Lewis and Kümmel[33] expressed the view that both the Franklin limestone and Pochuck gneiss were older than the granitoid gneisses, but that the original relations of the two are not now determinable. They believe that the Pochuck is probably in part igneous and in part sedimentary, but that apparently the dark rocks were foliated before invasion by the gneisses, because of the regularity of interlayering. The lamination of the Franklin limestone is thought by them to be mainly flow structure, deformation occurring simultaneously with the introduction of hot mineralizing waters from the Losee and Byram gneisses. They then conclude that the limestone, gneisses and enclosed ores "crystallized in their present state and received their present form and structures as geologic masses during a single period of regional deformation."

Possible Theories of Origin.—Among the possible theories which it seems to the writers could be advanced, the following may be mentioned:

1. Igneous injection. This is a possible one suggested by Spencer, but it is not accepted by him, and moreover such a mode of origin would not account for the admixture of ore minerals with grains of the Franklin limestone.

2. Sedimentary deposition, in other words, deposits of contemporaneous age with the associated limestone. The most weighty objection to this is the peculiar shape of the Sterling Hill deposit so far as developed, its structure as thus far known being not a single folded stratiform mass, but evidently consisting of one trough-shaped originally tabular mass with at least one branch splitting off from the west limb.

[32] N. J. Geol. Surv., Ann. Rept. of State Geologist, 1905, p. 173.
[33] N. J. Geol. Surv., Bull. 14, 1915.

3. Contact-metamorphic deposits. While at first sight the Mine Hill deposit may present some of the mineral characters of contact metamorphism, still there is no evidence that the silicates of the contact metamorphic type found in Mine Hill for example, and the ore minerals come from the same intrusive. Moreover it is quite clear that the ore minerals came first, and that the silicates followed the intrusion of the post-ore pegmatite. Furthermore, in Sterling Hill the silicates are absent at most points in the mine. Some writers, however, place the ore deposits in this class.[34]

4. Deposition by magmatic waters, by a process of replacment of the limestone. This view seems to be perhaps the one most generally accepted at the present. Even under this interpretation, the deposition may have taken place under one of two conditions, viz.: (*a*) Subsequent to the folding of the limestone, and (*b*) prior to the folding.

Certain objections to the first supposition appear to the writers. If it is the correct theory it means: first, that the ore-bearing solutions have followed certain beds in the limestone, which it seems hard to conceive in view of the fact that the country rock shows no difference in composition or texture along the line of the ore-mass; second, that one might expect the ore to spread out more into the trough between the two limbs than it does; third, one might expect to find some change in the limestone when followed away from the ore, which is not the case. It is true that here and there are found patches of fine-grained gray limestone in the coarser material, but so far as observed they show no connection with the ore; fourth, the thick mass of ore found in the bottom of the trough at Mine Hill is under such strain due to folding that it spalls off in the stopes. Had the limestone thus strained by folding been subsequently replaced by ore, it would seem that in the replacement process this strain would have been relieved, which has evidently not been the case.

[34] Lindgren, "Mineral Deposits," 2d ed., p. 753, calls them abnormal contact metamorphic deposits. Beyschlag, Vogt, and Krusch, "Ore Deposits," vol. 1, p. 394.

The authors are in agreement with the view that replacement occurred before folding.

Authors' Theory.—In endeavoring to formulate a satisfactory theory it is necessary to take into consideration all the structural and mineralogical features of the zinc-ore deposits. While some important evidence bearing on the problem has been obtained in the more recently developed portions of the ore-bodies and also from petrographic study of the ore, the writers do not hesitate to preface a statement of their theory by saying that there are still several points to be cleared up, some of which may never be satisfactorily settled due to lack of evidence. Indeed, future developments may cause the theory here advanced to be modified.

The sequence of events appears to the writers to be as follows:

1. Metamorphism of the Franklin limestone preceding the deposition of the ore. During this time it is probable that the juices from some igneous rock, possibly, as has been suggested, the Losee or Byram gneiss, produced the various minerals which are scattered through it, and which in many cases show no proximity to dikes or intrusive masses of any sort.

It is probable also that prior to or during this period the limestone was also intruded by basic dikes which are now represented by the foliated dark rocks found here and there in the limestone, the detached pieces representing fragments of dikes which have been torn apart by the profound early regional metamorphism that the limestone underwent.

The coarse rims of hornblende, pyrite, with garnet and sphene which are found bordering some of these masses may represent contact rims.

The pegmatites which were intruded into the limestone at a much later date suffered no such changes.[35]

2. Deposition of the ore minerals mainly by replacement of the limestone, though possibly in some cases in cavities. The order of deposition as outlined on an earlier page was tephroite and

[35] It may be of interest in this connection to refer to a paper by A. Laitakari, "Deposits of Crystalline Limestone of Kirmonniemi a Korpo," Finland., Com. Geol. Finland, Bull. 46, 1916.

willemite contemporaneous or nearly so, franklinite, zincite. It is not supposed that the periods of deposition were entirely separated, but that they probably overlapped somewhat, yet in the majority of cases the order of succession is not difficult to make out.

While the three zinc minerals, willemite, franklinite, and zincite, occur together only at Mine Hill and Sterling Hill, it would appear that some of the zinc-bearing solutions came up at other places, since willemite has been deposited in at least small quantities at one other locality, for Bayley has noted its occurrence in the Sulphur Hill magnetite mine near Andover.[36] The deposit is considered by Bayley to be a limestone replacement.

It is presumed that both the Mine Hill and Sterling Hill ore-bodies as first deposited consisted in the main of tabular masses, due to the fact that the ore-bearing solutions followed chiefly the bedding planes in the limestone. If they followed any fractures these have since been sealed.

As might be expected from the mode of deposition the ore is not everywhere equally rich, and moreover the solutions seem to have penetrated beyond the main channelway as shown by disseminated ore outside the main mass as in the walls of the "vein" at Mine Hill, the disseminated ore between the two limbs of the trough at Sterling Hill, and by the apparent branches of the west limb at the latter locality.

3. Intrusion of the syenite mass in the upper part of the Sterling Hill ore-body. This, as already remarked, has developed zinc and manganese-bearing silicates on the side towards the ore, a fact noted by Spencer.

4. Folding of the limestone with the ore-bodies, resulting in the development of the curious trough-shaped deposits at the two localities.

Since in those parts of the ore-bodies where the ore minerals show their normal order of succession as outlined above, the zincite is sometimes found filling the cracks in the fractured franklinite, one may question whether some of the folding had not

[36] Report on Iron Ores, N. J. Geol. Surv., vol. VII., p. 132.

begun before all of the ore minerals had been deposited. That the ores were folded after deposition seems to be shown by the strain which they are under in places, as in the bottom of the Mine Hill trough.

5. Intrusion of the pegmatite at Mine Hill, accompanied or followed by the deposition of silicates, and some recrystallization of the ore minerals near pegmatite contacts.

This stage in the process was referred to by Spencer.[37] That these many silicates and even other minerals were given off by the pegmatite is shown by the fact that they occur only near the pegmatite intrusions, and their later age than the ore minerals is indicated by the relations of the two as seen in thin sections. The evidence is also quite clear that the pegmatite juices must have reacted with some of the ore minerals to give the zinc and manganese-bearing silicates, for these are not found adjacent to the pegmatite where the ore minerals are absent.

Within these "zones of influence" of the pegmatite, cases are found where some of the ore minerals seem to be later than the silicates derived from the pegmatite, and it is highly probable that these represent products of recrystallization referred to by Spencer.

In addition to the pegmatite being the source of the great variety of non-metallic minerals found at Mine Hill, it is possibly also the source of certain metallic minerals such as native copper, chalcocite, native silver and niccolite. On this point we found no definite evidence except in the case of native copper, which is closely associated with the cyprine, the latter being supposedly derived from the pegmatite.

The syenite-monzonite in the 1,600 level of the Sterling Hill ore-body was also probably intruded after the folding although definite evidence of this is lacking, and the authors recognize the possibility that it may have been contemporaneous with the syenite exposed in the Calamine pit.

6. Deposition of later or secondary willemite in post-ore fractures, but whether due to solution and redeposition of earlier zinc ore minerals, or introduction of more zinc-bearing solutions the

[37] *Loc. cit.*

evidence is not as full as one might wish. An indication of the former is that the secondary willemite is sometimes developed as minute needles in the cracks of primary willemite but this is by no means always true. It has been suggested by Spencer that the solutions forming the willemite in veins came from the pegmatite, but if this were so, one might expect to find some of the other zinc-bearing silicates deposited in the same fractures. So fas as the writers have observed this is not the case. Whatever the nature of the process, the solutions which deposited the secondary willemite also in some cases at least seem to have deposited opaline silica for the two minerals are sometimes found in the same fracture. In such cases, however, the silica may form narrow bands along the walls of the crack. In one specimen at least opaline silica without the willemite was found.

7. Fracturing of the ore-bodies, accompanied in cases by faulting. The writers must confess their inability to decide on the basis of present evidence whether the faulting was all of one period or two. There are many small faults to be seen in Mine Hill and especially in Sterling Hill which clearly postdate the ore, but which are not traceable usually for more than a few feet, or sometimes only a few inches. In most cases they have been sealed. In Sterling Hill several instances were observed of coarse breccias, which seemed to be due to local squeezing without faulting, and which did not appear to offset the ore-body.

Certain faults like the large one along the eastern side of the Sterling Hill ore-body, and the local one in the west limb of the Mine Hill ore-body, north of the Palmer Shaft are undoubtedly of post-Kittatinny age.

8. Introduction of sphalerite, pyrite, and possibly galena and chalcopyrite. The first two of these minerals are likely to be found in small quantities in any part of either ore-body where there has been post-ore fracturing. In other words they do not show a close association with the pegmatite.

Since the sphalerite and pyrite are both found in the fault breccia associated with the post-Kittatinny fault in Mine Hill, one must assume that the introduction of these minerals into post-ore

fractures was of late date, or that there has been more than one period of deposition of the two sulphides.

If they are in all cases late introductions, then some of the galena and chalcopyrite in Mine Hill must also be of late age.

9. Deposition of carbonates. Some of the post-ore fractures at Mine Hill contain both calcite and dolomite, and the former appears to have attacked the willemite.

10. Intrusion of basic dikes of post-Ordovician age. These are represented by the large camptonite dike cutting across the ore-body at Mine Hill, and described by Wolff,[38] who mentions that there are 18 smaller ones. A number of others as yet undescribed occur in Sterling Hill.

11. Erosion and subsequent slight weathering of the minerals in the ore deposits as shown by the finding of calamine, smithsonite, and azurite.

MAGNETITE IN MINE HILL.

While this paper is concerned chiefly with the origin of the zinc ores, brief mention should be made of the magnetite body associated with the zinc ore in Mine Hill at Franklin.

Reference has already been made to the occurrence of magnetite in the pegmatite, but in addition, as already well known, there is a body of magnetite in the footwall limestone of the west limb of the zinc ore at Mine Hill. No special investigation of it was made by the writers, but it was seen at a number of points in the mine workings. It occurred usually in the white limestone, but in one place at least it was on the contact of the white limestone and the Pochuck gneiss. In places it formed a practically solid mass, rarely however over one foot in width, while at others it formed bands of grains thickly disseminated through the white limestone. While the magnetite and pegmatite were sometimes seen in contact, they were sharply separated and neither was observed to cut across the other.

Where the magnetite was seen in a number of cross cuts on the

[38] U. S. Geol. Atlas Folio, 161.

750 and 800 level it was found to run practically parallel with the zinc ore-body, and a drift run on the 800 level around the end of the basin showed that to that point at least the magnetite was curving around with the ore. Bore holes put down approximately along the line of the east limb of the zinc ore struck the magnetite about 1,800 feet north of the big camptonite dike.[39]

Judging from what field evidence we have, and from subsequent laboratory study, it would seem that the magnetite at Mine Hill occurs both as a replacement of the limestone and as a constituent of the pegmatite.

Assuming this statement of genesis to be correct we have not yet been able to make out the spatial relationships of the two kinds of magnetite. There is a possibility that the limestone replacement magnetite was formed prior to the folding of the limestone and possibly may be correlated with the zinc ore-bodies, since their genesis is strikingly similar, and that the magnetite of the pegmatite postdates the period of limestone folding.

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[39] Nason, Amer. Inst. Min. Engrs., Trans., XXIV., p. 121, 1894.

ANALYSIS OF STRUCTURE BELOW AN UNCONFORMITY.[1]

J. B. Mertie, Jr.

Structural unconformities are stratigraphic criteria of the first order, and deserve to be scrutinized carefully. The purpose of this paper is to point out a simple method of interpreting the structural data available from an unconformable relationship of geologic strata.

If the beds above and below an unconformity are both tilted, it is evident that the direction and amount of inclination of the underlying beds is the combined result of two distinct periods of deformation. This composite tilt may be resolved into two components, corresponding to the two deformations, and in this way the attitude of the lower beds previous to the second period of folding may be deciphered. If sufficient data of this kind are available, the regional pre-unconformity structure may be worked out. Likewise in certain fault problems, where tilted blocks owe their position to two or more movements, the principle may also be used to advantage.

The principle involved is not new. Harker,[2] in 1884, considered the problem as follows: "Strata having a dip given in direction and amount receive a secondary tilt given in direction and amount; to find the direction and amount of the resulting dip." He gave, without proof or discussion, a formula suitable for derivation of the pre-unconformity dip, but not for the strike. Incidentally, he and others writing in the *Geological Magazine* at that time considered graphic solutions of other stratigraphic problems, which appear to have been generally overlooked.

The simplicity of the problem is apparent when considered as an application of spherical trigonometry. In Fig. 51, two per-

[1] Published by permission of the Director of the U. S. Geological Survey.

[2] Harker, Alfred, "Graphical Methods in Field Geology," *The Geological Magazine*, New Series, Decade III., Vol. 1, 1884, pp. 154–162.

spective drawings of spherical triangles are given, illustrating two possible cases, *i.e.*, (*A*) where the beds above and below an unconformity dip in the same direction with regard to the vertical, and (*B*) where they dip in opposite directions.

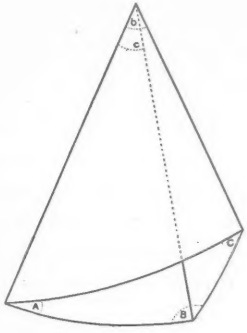

FIG. 51 *A*.

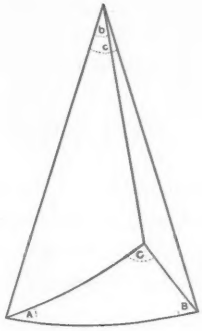

FIG. 51 *B*.

In the spherical triangle represented by Fig. 51, *A*, let the stratigraphic data be represented as follows:

Let A = Present angle of dip of the beds above an unconformity.

B = The supplement of the present angle of dip of the beds below an unconformity.

c = The angle between the strike of the upper and lower beds.

By rotating the figure until the plane of the spherical angle b becomes horizontal, it will be seen that the angle C represents the dip of the lower beds prior to their second deformation, and that the angle b represents the angular difference between the present strike of the upper beds and the strike of the lower beds prior to their second deformation. Fig. 51, *B* shows the same relationship, except that B represents the present dip of the lower beds instead of its supplement, and C represents either the pre-unconformity dip of the lower beds, when C is acute, or its supplement, when C is obtuse. The solution of this problem is therefore the solution of an oblique spherical triangle.

The value of C may be obtained from the following spherical triangle formula:

$$\cos C = \sin A \sin B \cos c - \cos A \cos B. \qquad (1)$$

After C is obtained, the angle b may be obtained from either of the two following formulas:

$$\cos b = \frac{\cos A \cos C + \cos B}{\sin A \sin C}, \qquad (2)$$

$$\cot b = \frac{\sin A \cot B + \cos A \cos c}{\sin c}. \qquad (3)$$

Equations (1), (2), and (3) could, if desired, be plotted as four-variable alignment charts, but in view of the relative infrequency with which they will be used, it seems to the writer that solutions by logarithms or slide rule will be more practical.

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THE GEOLOGIC AND GEOGRAPHIC OCCURRENCE OF PRECIOUS STONES.[1]

SYDNEY H. BALL.

"In the mountains of Serendib (Ceylon) precious stones are found, of various colors, red, green and yellow, most of which are washed from caverns or crevices by rains and torrents. . . . In some places these are dug out of veins like the ores of metals and the rock has often to be broken to come at the precious stones which it contains."—Abu Zeid al Hasan, 850 A.D.

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INTRODUCTION.

Although the geology of metallic minerals has been exhaustively studied, but little attention has been paid to the occurrence of precious stones. In these notes regarding the geology of precious stones, only such localities and occurrences as have furnished material to the jewelry trade are considered. The figures used in the tables are the assumed value of the rough product at the mine. No great accuracy is claimed for them, and in the case of some of the minor precious stones, they are little more than guesses. For instance, Colombia at present is not producing emeralds to the value stated, but as it is the principal source of that gem, future production will presumably approximate the

[1] Presented before the Society of Economic Geologists, December 29, 1921.

figure of past production here given. Data on which generalizations have been made is presented so that the validity of the generalizations may be weighed by the individual reader. Most of the statistics are necessarily those of pre-war times.

Mineralogists may well object to including in the tables nephrite and jadeite, which, in most instances at least, are rocks rather than minerals, and the fossil substances amber, jet and bone turquoise.

RELATIVE PRODUCTION OF VARIOUS PRECIOUS STONES.

The world's production of rough gems in normal years is worth annually some $80,696,000; of the total, the diamond accounts for 94.3 per cent.; and sapphire, amber, emerald, ruby, jadeite, turquoise and opal together another 4.6 per cent. (Table I. and Fig. 52).

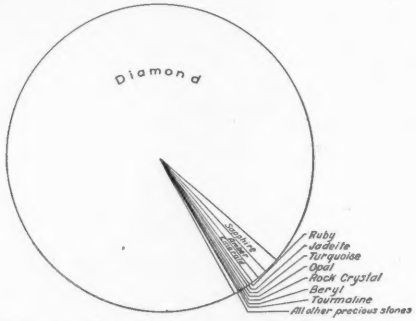

FIG. 52. Diagram showing relative yearly production of various precious stones. 1° equals approximately $225,000.

TABLE I.

Diamonds	$76,112,500
Sapphire	1,210,000
Amber	800,000
Emerald	550,000
Ruby	365,000
Jadeite	294,000
Turquoise	290,000
Opal	209,000

Rock crystal	110,000
Beryl	100,000
Tourmaline	90,000
Amethyst	82,000
Agate (chalcedony, etc.)	71,000
Garnet	68,000
Nephrite	66,000
Lapis lazuli	50,000
Cymophane	50,000
Spinel	20,000
Topaz	20,000
Jet	20,000
Olivine	15,000
Rose quartz	12,000
Spodumene	10,000
Gold quartz	10,000
Zircon	7,100
Moonstone	5,000
Tiger-eye	5,000
Chrysoprase	5,000
Cairngorm	5,000
Bone turquoise	5,000
From $1,000 to $5,000 annually: [2] Amazonstone, benitoite, cat's-eye (quartz), chrysocolla, cyanite, euclase, fluorspar, jasper, labradorite, malachite, phenacite, pyrite, rhodonite, variscite, vesuvianite	28,000
Under $1,000 annually: [2] Anatase, andalusite, apatite, aventurine, axinite, azurite, bronzite, calamine, cordierite, danburite, datolite, diopside, dioptase, elæolite, enstatite, epidote, haüynite, hematite, hemimorphite, hypersthene, kornerupine, microlite, obsidian, prehnite, rutile, sapphirine, satin spar (calcite), satin spar (gypsum), scapolite, sillimanite smithsonite, sodalite, sphene, staurolite, thompsonite, willemite	10,600
Total	$80,696,000

After being cut, the cost of precious stones to the ultimate consumer is from two to three times the figures given.

GEOGRAPHICAL DISTRIBUTION.

The map (Fig. 53) shows the principal gem localities. It potently refutes the view held by the ancients and, indeed, by some

[2] Alphabetically arranged.

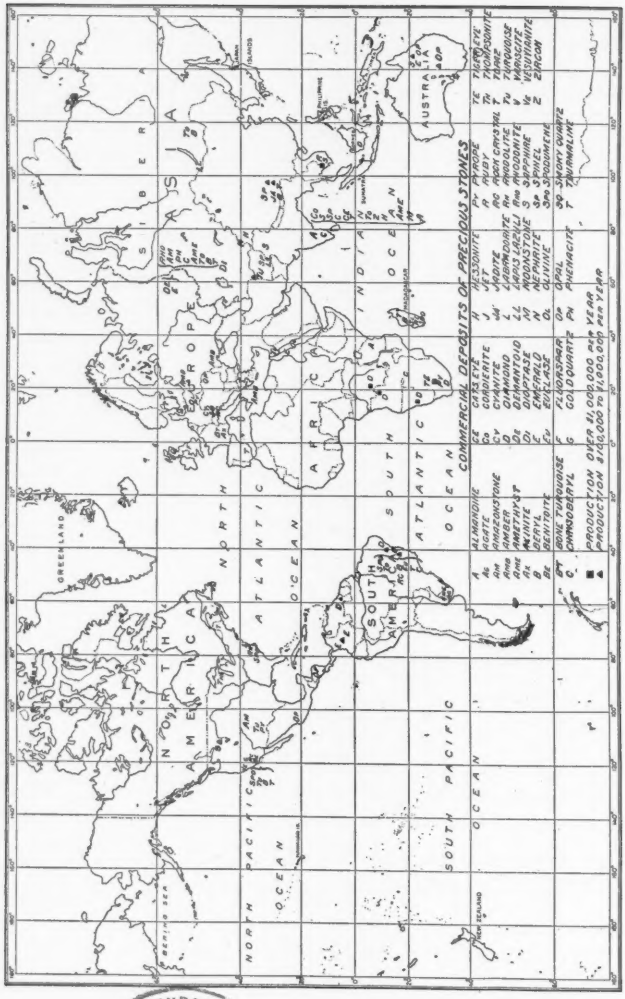

FIG. 53.

KANSAS STATE AGRICULTURAL COLLEGE LIBRARY NOV 13 1922

gem authorities of 50 years ago,[3] that gems are particularly common in the tropics. As the ancients obtained most of their precious stones from India, the origin of the myth is evident.

Climate, however, is an important factor in the distribution of a few precious stones. Turquoise, like the principal disseminated copper ore bodies, is confined to arid or semi-arid regions, and olivine, which so readily alters, is usually found either in very fresh rock or as detrital material in desert regions.

Production by Countries.—With the exception of the diamond, ruby, sapphire, amber and emerald, gems are produced by small companies or individual miners, and many of the latter mine gems in only a desultory way, frequently engaging in farming or some other industry for the major portion of their time. As a result, the production of each country varies greatly from year to year and even in the most important gem-producing countries, like South Africa, the variable demand for the product causes wide fluctuations in the yearly output. As an example, the production of the United States from 1913 to 1918, according to the Federal geological survey, ranged from $106,523 to $319,454, the average being $168,803.

The approximate importance of the various countries as sources of precious stones follows (also Fig. 54).

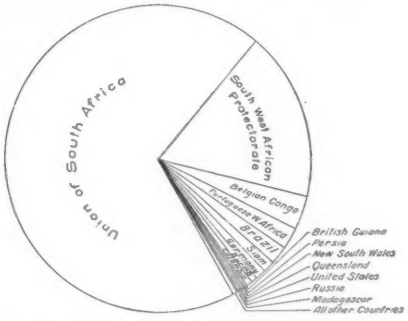

FIG. 54. Diagram showing production by countries. 1° equals approximately $225,000.

[3] L. Feuchtwanger, "A Popular Treatise on Gems," 4th edition, 1872, page 146.

TABLE II.

PRODUCTION BY COUNTRIES.

Union of South Africa	$55,520,000	Madagascar	150,000
South African Protectorate	14,350,000	Chinese Turkestan	95,000
Belgian Congo	2,800,000	Ceylon	80,000
Portuguese West Africa	1,800,000	India	60,000
Brazil	1,500,000	Borneo	50,000
Siam	975,000	Czecho-Slovakia	37,000
Germany	790,000	France	30,000
Burma	580,000	Great Britain	27,500
Colombia	500,000	Japan	25,000
British Guiana	250,000	Egypt	25,000
Persia	200,000	China	25,000
New South Wales	180,000	Afghanistan	23,000
Queensland	180,000	Uruguay	20,000
United States	175,000	Other Countries	78,500
Russia	170,000		$80,696,000

It will be observed that the first five countries tabulated produce diamonds, although Brazil also produces perhaps $80,000 worth of other gems. The continents rank as follows:

Africa	$74,653,500	or 92.5%
South America	2,270,000	or 2.8%
Asia	2,123,000	or 2.6%
Europe	1,094,500	or 1.3%
Australia	360,000	or 0.4%
North America	195,000	or 0.3%
British possessions and mandates produce ..... of the world's precious stone output.	71,272,000	or 88 %

The continents produce annually precious stones other than diamond as follows:

Asia	$2,072,000
Europe	1,094,500
South America	654,000
Australia	353,000
Africa	196,500
North America	192,500

GEOLOGIC OCCURRENCE.

Except in the diamond, emerald and sapphire industries carried on by large corporations, hard-rock mining has rarely been suc-

cessful. Jadeite in Burma is, nevertheless, in part quarried, and the natives of Kashmir profitably mined sapphires in a fresh granite; the portion worked, however, contained an unusual gem content. Gem mining in pegmatite dikes usually ceases after the weathered zone has been penetrated, although locally precious stones are obtained from fresh pegmatite dikes as a by-product of other types of mining, mica mining for example.

Tables III. and IV. and Figs. 55 and 56 attempt to show the

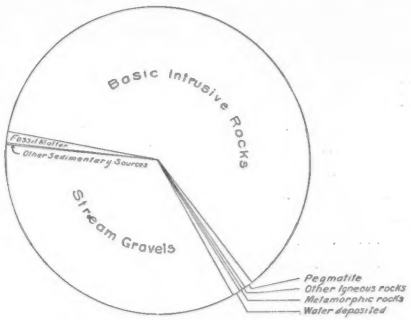

FIG. 55. Diagram showing geologic source of all precious stones as to value. 1° equals approximately $225,000.

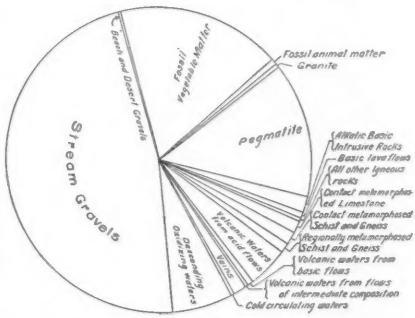

FIG. 56. Diagram showing sources of all precious stones, as to value, except diamonds. 1° equals approximately $12,750.

geologic sources of precious stones quantitatively. Many precious stones occur under conditions not tabulated, but such are not com-

mercial sources. In some instances, the descriptions in the literature are so faulty or so incomplete, particularly those referring to the less used precious stones, that doubtless the table contains errors.

TABLE III.

TABLE SHOWING APPROXIMATE ANNUAL VALUE OF PRECIOUS STONES AS TO SOURCE.

Meteorites—bronzite, diamond, diopside, quartz, apatite, enstatite, hypersthene, olivine, zircon and sapphire.			
Granite—sapphire,[6] zircon.[6]			
		Total value, $	12,500
Pegmatite—			
Emerald	$ 520,000		
Beryl[4]	46,000		
Tourmaline[5]	35,000		
Rock crystal[6]	11,000		
Rose quartz[4]	11,000		
Spodumene	9,500		
Topaz[5]	8,800		
Amethyst[6]	7,000		
Moonstone[4]	4,000		
Cairngorm[4]	3,000		
Cymophane[6]	2,000		
Amazonstone, anatase, euclase,[4] cordierite, phenacite, rutile,[5] essonite,[4] aventurine,[4] axinite, spessartite, scapolite, kornerupine, apatite, cyanite,[6] danburite, microlite, sphene, sapphire,[6] ruby, diamond (?), diopside, zircon[6]	4,700		
		Total, $	662,000
Acid lava flows—			
Obsidian	500	Total,	500
Alkalic syenite—			
Melanite, elæolite, haüynite, sodalite, zircon[6] .			1,000
Augite andesite—			
Sapphire	10,000		10,000
Alkalic basic intrusive rocks—			
Sapphire[6]	70,000		70,000

Basic intrusive rocks—			
Diamonds [5]	50,000,000		
Pyrope [4]	3,000		
Rhodolite,[4] hypersthene,[4] olivine,[6] enstatite, labradorite,[4] ruby, diopside	1,500		
		50,004,500	
Basic lava flows—			
Sapphire [6]	12,500		
Olivine [6]	9,000		
Ruby [6]	3,000		
		24,500	
TOTAL IGNEOUS ROCKS			$50,785,000
Contact metamorphosed limestone—			
Lapis lazuli [4]	37,500		
Ruby [5]	13,500		
Spinel [6]	2,000		
Tourmaline, sapphire,[6] grossularite,[4] vesuvianite,[6] sphene, epidote, willemite, apatite	3,500		
		Total, 56,500	
Contact metamorphosed schists and gneisses—			
Jadeite [4]	150,000		
Emerald	20,000		
Cymophane [6]	4,000		
Cyanite,[6] phenacite, staurolite,[4] diopside, andalusite,[4] jasper,[6] cordierite, tourmaline	1,500		
		Total, 175,500	
Regionally metamorphosed schists and gneisses—			
Nephrite [4]	30,000		
Almandine [4]	10,000		
Tiger eye	5,000		
Vesuvianite [6]	2,000		
Demantoid [4]	2,000		
Epidote, jasper, cyanite,[6] sillimanite,[4] sapphirine,[4] sapphire, anatase, ruby, cordierite	1,000		
		Total, 50,000	
TOTAL METAMORPHIC ROCKS			$ 282,000

Volcanic waters from acid flow rocks—			
Opal	192,000 (a)		
Variscite	3,000		
Topaz, spessartite	1,000		
		Total,	196,000
Volcanic waters from flow rocks of intermediate composition (andesite and trachyte)—			
Opal			14,000
Volcanic waters from basic flow rocks—			
Agate [6]	12,000		
Amethyst [6]	10,000		
Opal	2,500		
Thompsonite,[4] prehnite,[4] datolite	700		
		Total,	25,200
Veins deposited by magmatic waters—			
Amethyst [6]	25,000		
Rock crystal [6]	11,000		
Gold quartz	10,000		
Fluorspar	2,000		
Rhodonite	2,000		
Benitoite	1,800		
Uvarovite,[4] epidote, pyrite, hematite, apatite, chrysoprase, diamond (?) prase, topaz	2,000		
		Total,	53,800
Cold circulating waters—			
Agate	3,000		
Jasper [5]	1,000		
Pyrite, satin spar (gypsum), satin spar (calcite), hematite quartz	1,500		
		Total,	5,500
Descending oxidizing waters—			
Turquoise	290,000		
Chrysoprase	5,000		
Malachite	3,000		
Chrysocolla	1,000		
Azurite, dioptase, hemimorphite, calamine, smithsonite, opal	1,500		
		Total,	300,500
TOTAL BY WATER			$ 595,000

[4] denotes only original source; [5] only important source; [6] important original source.

a: Although evidence is not satisfactory, practically all of New South Wales and Queensland production is here provisionally referred to rhyolite.

Fossil vegetable matter—				
Amber	800,000			
Jet	20,000		820,000	
Fossil animal matter—				
Bone turquoise	5,000		5,000	
TOTAL FOSSIL MATTER				$ 825,000
Stream gravels—				
Diamond	26,112,500	Emerald		10,000
Sapphire	1,104,000	Zircon		7,000
Ruby	348,500	Essonite		4,500
Jadeite	144,000	Cat's-eye (quartz)		3,000
Rock crystal	88,000	Demantoid		3,000
Tourmaline	54,000	Olivine		2,000
Beryl	54,000	Jasper		2,000
Agate	53,000	Cairngorm		2,000
Cymophane	44,000	Rhodolite		1,600
Amethyst	40,000	Moonstone, rose quartz, cordierite, spodumene, grossularite, vesuvianite, sillimanite, cyanite, rutile, euclase, staurolite, andalusite, aventurine		5,700
Nephrite	36,000			
Pyrope	24,000			
Spinel	18,000			
Almandine	15,000			
Lapis lazuli	12,500			
Topaz	11,000		$28,199,300	
Beach gravels—				
Agate	3,000			
Nephrite, labradorite, jasper, hypersthene, prehnite, thompsonite	1,200			
			4,200	
Glacial deposits—				
Diamond, labradorite, nephrite			—	
Desert gravels—				
Olivine	3,850			
Pyrope, jasper	1,650		5,500	
TOTAL SECONDARY DEPOSITS				$28,209,000
GRAND TOTAL				$80,696,000

Note: The lesser minerals are named in the approximate order of the magnitude of their production.

TABLE IV.

TABLE SHOWING SOURCE OF ALL GEMS EXCEPT DIAMOND.

Granite	$ 12,500
Pegmatite	662,000
Acid lava flows	500

Alkalic syenite	1,000	
Augite andesite	10,000	
Alkalic basic intrusive rocks	70,000	
Basic intrusive rocks	4,500	
Basic lava flows	24,500	
TOTAL IGNEOUS		$ 785,000
Contact metamorphosed limestone	56,500	
Contact metamorphosed schist and gneiss	175,500	
Regionally metamorphosed schist and gneiss	50,000	
TOTAL METAMORPHIC ROCK		282,000
Volcanic waters from acid flow rocks	196,000	
Volcanic waters from flow rocks of intermediate composition	14,000	
Volcanic waters from basic flow rocks	25,200	
Veins deposited by magmatic waters	53,800	
Cold circulating waters	5,500	
Descending oxidizing waters	300,500	
TOTAL BY WATER		595,000
Fossil vegetable matter	820,000	
Fossil animal matter	5,000	
TOTAL FOSSIL MATTER		825,000
Stream gravels	2,086,800	
Beach gravels	4,200	
Desert gravels	5,500	
TOTAL SECONDARY DEPOSITS		$2,096,500
GRAND TOTAL		$4,583,500

Igneous Rocks as Source.—Due to the preponderant position of the South African kimberlite pipes as diamond producers, the basic igneous intrusive rocks are the most important original source. Incidentally these pipes characterize a vast petrographic province in southern Africa, from the Belgian Congo localities (10° S.) to the Orange River (30° S.), a distance of 1,300 miles. Such an extensive precious stone-bearing petrographic province, if we may use the phrase, is unique.

South Africa is also the only country in which diamonds are definitely known to be derived from more than one original source. In addition to the main source, the pipes, the Witwatersrand banket (Cambrian or pre-Cambrian) contains detrital diamonds, and diamonds also occur in a Vaal River amygdaloidal andesite, presumably a member of the Ventersdorp Series (early

Paleozoic). In 1920, the Witwatersrand gold mines produced 61 carats of diamonds worth $1,076.

Sapphire also occurs in two different rocks in a restricted geographic area in Montana, where it is an original constituent of two dike rocks, monchiquite-camptonite and mica-augite-andesite.

Granite pegmatite, which furnishes a variety of different precious stones, is the only other igneous rock which is an important source of precious stones. The gem-bearing pegmatites are usually of coarse, and frequently of very coarse grain, and contain miarolitic openings, the walls of which may contain well-crystallized precious stones. At Schneckenstein, Saxony, topaz, with some cassiterite, partially fills breccia cavities. This presumably is a high temperature vein deposit rather than a pegmatite, but it may be mentioned that its druses are known among the miners as "Topasmütter." Several adjacent dikes are, in many instances, gem-bearing, forming gem mining centers. The pegmatites which contain precious stones are usually quartz-rich and the original magma presumably contained large quantities of gases. Only certain portions contain precious stones, and these portions frequently contain minerals not occurring in the main pegmatitic mass. In both Maine and Southern California garnet-rich rocks occur near the gem-bearing portion.

The gem-bearing pegmatites, as noted by several authorities, are of two types, the potash-rich and the soda-lithia-rich. In certain fields, only one type is present, although the more important gem-bearing pegmatitic regions have both. The former produces blue beryl and topaz, while in the latter occur colored tourmalines and kunzite, and frequently pink beryl. The soda-lithia pegmatites are characterized by the almost constant presence of lepidolite and in large pegmatitic bodies, where the normal mica is muscovite, and the normal tourmaline is black, small masses may contain lepidolite, in which phase the tourmaline is probably without exception red, blue or green. In the soda-lithia pegmatites, the characteristic feldspar is albite, although either microcline or oligoclase may also be present. Other common constit-

uents are spodumene, amblygonite, columbite and pitchblende, or its alteration products. Smoky quartz is also characteristic of numerous pegmatites of this type. W. E. Ford[7] states that the pink or white beryl of this type of pegmatite is as a rule of short habit inclining to tabular rather than the columnar crystal common to beryl. L. DuParc[8] made the same observation regarding the crystal forms of beryls in the two types of pegmatite producing gems in Madagascar. Both the beryl and the colored tourmalines are rich in lithium and the beryl, in addition, frequently contains cæsium. The soda-lithia pegmatites are the source of all gem tourmalines with the exception of a few brown, grass-green and yellow tourmalines which occur in contact-metamorphic limestone.

The gem-bearing pegmatites of San Diego and Riverside counties, California,[9] are intrusive in biotite granite and gabbro, the gem-bearing pegmatitic masses occurring particularly in the latter rock. Only certain of the numerous dikes contain precious stones, and usually several such dikes are near one another, forming gem mining centers. The pegmatites are typically coarse aggregates of quartz, orthoclase and muscovite with some black tourmaline. In such pegmatites, topaz, blue beryl, and garnet (spessartite) may be accessories.

In certain dikes and also in portions of normal pegmatite dikes, albite occurs, lepidolite is common, and amblygonite may be present, resulting in a soda-lithia-rich rock in which the black tourmaline is replaced by red, blue or green tourmaline, and lilac spodumene (kunzite) occurs. These pegmatites usually consist of an upper layer of coarse pegmatite and a lower fine-grained layer, rich in feldspar, in which are laminæ containing many small brown garnet crystals or, less commonly, small blue or black tourmaline columns. Along the contact of these two types of pegmatite are miarolitic cavities in which the gems occur, ac-

[7] *Am. Jr. Sc.*, Series 4, vol. 22, pages 217 to 233.

[8] *Bul. Soc. Franc. de Min.*, t. 34, 1911, pages 131 to 139.

[9] Chief references: Geo. F. Kunz, Bull. No. 37, California State Mining Bu., 1905. G. A. Waring, *Am. Geol.*, 1905, pp. 356-69. Waldemar T. Schaller, Univ. of Cal. Publications, vol. 3, no. 13, pages 265-75.

companied by albite, lepidolite and quartz. These minerals either lie in clay or are attached to the walls, although in instances they are intergrown with the quartz or orthoclase forming the walls of the cavities. Kunzite, unlike tourmaline, rests on the other minerals and hence is presumably the last mineral to crystallize.

The granite pegmatites of Maine[10] of late Silurian or Devonian age intrude schists and gneisses and have long been one of the principal sources of colored tourmalines. Colored tourmalines occur in two areas of soda-lithia-rich pegmatite in Androscoggin and Oxford counties, the larger being twenty-five miles long and about nine miles wide. To the west are other pegmatites without lithium content, or with only slight traces, in which aquamarine and topaz occur. Within these three areas several gem-bearing pegmatites occur near one another and several such groups characterize each gem-bearing area. The colored tourmaline-bearing pegmatites are of coarse grain; they tend to have a banded structure, the gems being largely confined to numerous miarolitic openings. The principal minerals are quartz, potash feldspar and muscovite, and in addition some lepidolite, albite (variety cleavelandite), spodumene and amblygonite. The colored tourmalines are confined to relatively small portions of the main pegmatitic mass in which the last-mentioned four minerals are abundant, that is, to a soda-lithia-rich phase. Such portions are usually sheet-like in form and parallel the greatest diameter of the pegmatite lens. Bastin states that a highly garnetiferous band separates the normal from the soda-lithia-rich pegmatite. The quartz is frequently smoky. Other constituents noted at certain localities are purple apatite and the secondary uranium minerals, gummite and autunite. At places the beryl is pink or white and is alkali-rich, the former type containing cæsium.

Madagascar[11] for the last twenty years has been a considerable

[10] Edson S. Bastin, U. S. Geol. Surv. Bull. 445; W. Rogers Wade, *Eng. and Min. Jour.*, June 5, 1909, pp. 1127–9.

[11] Particularly M. A. Lacroix, *Bul. Soc. Franc. de Min.*, vol. 31, 1908, pp. 218–47; *Revue Scientifique*, June 25, 1921, pp. 321–29 and July 9, 1921, pp. 353–61 and M. D. Levat, "Richesses Minerales de Madagascar," pp. 171–91, Paris, 1912.

producer of precious stones. The principal sources are stream gravels and weathered outcrops, particularly those of pegmatite. From the stream gravels, sapphire, ruby, garnets, chrysoberyl, zircon, spinel and topaz are obtained, and, as usual, these stones are superior to those obtained from solid rock. In the weathered outcrops of schists and gneisses, almandine garnets are found and cordierite occurs either in pegmatitic quartz or in schists near pegmatitic intrusions. Sapphire, ruby and zircon have as their source basaltic rocks, and agate and chalcedony occur in their amygdules. Opal, of little economic value, occurs in a trachytic rock, and veins in quartzite are at least one source of rock crystal.

By far the greatest number of the island's gems, however, are derived from the weathered outcrops of pegmatites. The gem-bearing pegmatites occur in the central portion of the island in a country of alternating bands of limestone, mica schist, quartzite and gneiss, which strike from north to south. The gem-bearing pegmatites are coarse in grain, poor in mica and contain many miarolitic openings. The gem-bearing dikes occur in several different groups. Lacroix recognizes two types of pegmatites, the potash- and the soda-lithia pegmatite. The first consists of rose quartz, potash feldspar and mica (largely muscovite, some biotite) and produces bluish-green beryl, rose quartz, topaz and almandine-spessartite garnet. The micas of the soda-lithia pegmatite are lepidolite, zinnwaldite and biotite. It also contains albite, microcline and oligoclase; and furnishes, particularly from its miarolitic cavities, colored tourmalines (red, blue, green and yellow), rose beryl (morganite, rich in cæsium), kunzite, amazonstone, spessartite and danburite. In certain of the miarolitic cavities, the colored tourmaline and rose beryl appear to be of a later generation than the other constituent of the pegmatite. Diopside, chrysoberyl, amethyst, kornerupine, zircon and scapolite also occur in pegmatites. The uranium minerals include pitchblende, autunite and hatchettolite.

The North Carolina pegmatites contain no lepidolite, and are intrusive largely in Archean rocks, especially Carolina gneiss and

Roan gneiss. The chief minerals are quartz, feldspar and muscovite. The gems include beryl, essonite, quartz, albite, orthoclase, oligoclase and zinc spinel. In an isolated case, the green spodumene, hiddenite, is present. As G. F. Kunz has remarked, the non-lepidolite-bearing pegmatites of North Carolina contain green beryl and green spodumene, and the lepidolite-bearing pegmatites of Southern California, rose beryl (morganite) and lilac spodumene (kunzite).

All geologists may not consider the emerald-bearing veins of Muzo, Colombia, pegmatitic, but the best descriptions indicate that these veins were deposited by attenuated pegmatitic waters and in many of the minor occurrences of emeralds, including at least one other Colombian locality, the stone occurs in typical pegmatite. Douglas B. Sterrett[12] suggests that the coloring matter of the emeralds of the Turner mine, North Carolina, is derived through partial absorption of chromium-bearing basic rocks by the pegmatite intrusive in them. Serpentine occurs near the ancient emerald mines of Northern Etbai, Egypt,[13] and it exists near some of the Ural emerald mines.

Metamorphic Rocks as Source.—Contact-metamorphic limestone and contact-metamorphic schist and gneiss as ultimate sources of precious stones are of equal importance, each exceeding the regionally metamorphosed schist and gneiss. The contact metamorphic limestone is usually marble and not the more impure ("garnetite") variety.

Sedimentary Rock Occurrences.—With the exception of the two fossil vegetable substances, amber and jet, old sedimentary rocks are negligible sources of gems. Ancient gem gravels similar to "fossil" gold placers exist but are unimportant, although a conglomeratic sandstone of Carboniferous age at Grao Mogol, Brazil, was formerly exploited for diamonds, and in Burma, jadeite is mined from a well-cemented conglomerate. The agate and the carnelian of Ratanpur, India,[14] occur in Tertiary con-

[12] "Mineral Resources of U. S.," 1911, pp. 1051–8.

[13] Donald A. MacAlister, *Geog. Jnl.*, vol. 16, 1900, pp. 537–49.

[14] P. N. Bose, *Rec. Geol. Sur. of India*, vol. 37, part II., pp. 176–182.

glomerate, which is derived from the distintegration of amygdaloidal basaltic flows. Hans Oehmichen[15] states that the Bohemian garnet is an original constituent of inclusions of lherzolite caught up in a volcanic breccia, but that the principal commercial sources are stream gravels and Tertiary conglomerates. Certain of the garnets, therefore, have suffered three transportations; they were brought to the surface by volcanic breccia from which, through erosion, they entered the Tertiary conglomerate, and lastly they were deposited in the present-day stream gravels.

Stream gravels including both present and terrace gravels are by far the most important secondary sources of gems. Certain terrace gem gravels are high above the present streams, for example, the sapphire-bearing "bars" of the Missouri River (from 100 to 200 feet above river level) and some of the Vaal River diamondiferous gravel (400 ft.). Precious stones which are not present in the rocks of a drainage basin in sufficient quantity to pay for mining may be so concentrated in stream gravel, because of their heaviness, hardness and toughness, and with some exceptions, chemical inertness, that they may be mined profitably. As in gold placers, the richest gravel is immediately above bed rock and in its depressions; in the latter unusually rich gravel may occur. A high degree of concentration of the gems is usually required to make the gravels profitable. In consequence, gem gravels are particularly common in the tropics where weathering is relatively rapid and where the stream gravels are often composed of the heaviest and most resistant minerals of great thicknesses of rocks which have been removed by erosion. The heavier minerals are naturally transported shorter distances than the lighter and in consequence are more apt to occur near the rock source, while only the lighter gems may be found well downstream. Some of the precious constituents of the gravel are well rounded while others retain their crystal form. The latter are called by the Sinhalese gem-hunters "Yakunkapapu" or "devil cut" as they believe the faces have been produced artificially.[16]

[15] *Zeitschrift für prak. Geol.*, 1900, pp. 1–13.

[16] A. K. Coomaroswanny, Ceylon Administration Report for 1905, p. E. 18.

Even the intensely hard diamond is, in instances, water worn and in certain cases highly so; J. R. Sutton says[17]

"I have seen a Vaal River diamond worn as round and as rough as a marble with scarce a trace of its original surface left."

In gem gravels, different precious stones from different original sources are often associated. This is notably the case in Ceylon,[18] which, although not at present an important producer of precious stones, is interesting because of the variety of its product. The schists, gneisses and limestones composing the southern half of the island have been subjected to erosion under tropical conditions for a long time, possibly since the Archean, resulting in highly concentrated gravels. Moonstone is mined from pegmatite in the central portion of the island and a few garnets are obtained from decomposed gneiss, but the other precious stones are washed from the gravels of the present and ancient streams in the southwestern portion of the island. They include sapphire, star sapphire, ruby, yellow and white sapphire, chrysoberyl (ordinary chrysoberyl, cat's-eye and alexandrite), spinel, zircon, topaz, garnets (almandine and essonite), beryl, tourmaline, titanite, rutile, cordierite, sillimanite, andalusite, diopside, apatite and cat's-eye and several other varieties of quartz. The assemblage of the precious stones varies from stream to stream and is dependent upon the rocks of its drainage area. The apparent sources of the precious stones follow: from crystalline limestone, sapphire (in part), ruby, spinel (in part), zircon (in part), apatite, diopside, titanite and garnet (in part); from pegmatites, zircon (in part), tourmaline and beryl; and from gneisses and schists, sapphire (in part), garnet, sillimanite, andalusite, cordierite, zircon (in part), spinel (in part), and garnet (in part). The gems are especially abundant in the lower portion of the gravel, particularly in depressions in the bed rock. They are as a rule not greatly rounded. Gold, monazite and thorianite occur with the precious stones.

[17] *Transactions Royal Society South Africa*, vol. 8, 1919–1920, p. 135.

[18] Largely from A. K. Coomaroswanny (Ceylon Administration Reports for 1904, vol. II, E. II–19 etc.); Fr. Grunling (*Zeit. fur Kryst. und Min.*, vol. 33, 1900, p. 230–etc.); J. E. Tennent, Ceylon, pp. 31–40.

Some of the primitive people who mine alluvial gems believe that the precious stones grow in the stream gravels, owing to the fact that streams washed and presumably exhausted by one generation of gem hunters are found by gem hunters of the following generation to contain precious stones. The explanation is of course that the rivers bring down from up-stream a further supply of gems, and that in addition a certain number of gems weather from boulders in the river gravels.

Alluvial precious stones are on the average of better quality than those found in rock, for, if the gems contain incipient fractures or inclusions, they are broken along such planes of weakness as they travel downstream. Further in winning precious stones from gravel, there is little or no fracturing, a danger ever present in milling rocks. River diamonds bring unusually high prices, those of South Africa, for example, in 1920, having been sold for 220s. 6d. per carat as opposed to a price of 106s. 3d. for the stones from the kimberlite pipes.

At the Kuen Lun Mountains, Chinese Turkestan, nephrite locality, the river stones are freer from fractures and flaws, thus reducing the danger of the stone's splitting along some plane of weakness, particularly after it has been half carved. The perturbation of the artist may well be understood when it is realized that the better years of certain artists' careers have been spent on a single jade carving. Robt. Shaw[19] reports that the price of the "Soo Tash" or "water stones" was three times that of the quarry nephrite.

Beach gravels because of their relatively imperfect concentration are unimportant except as a source of amber.

In the early days of the Southwest African Protectorate diamond industry, wind concentration was important. Many thousands of carats were "mined" by Kaffir "boys" who picked up the stones as they laboriously crawled on hands and knees over sand dunes. P. A. Wagner[20] says:

> The uppermost portion of the deposit, which as a rule has been lashed by the force of the wind into regular waves or miniature dunes, is al-

[19] "Visits to High Tartary, Yarkand and Kashgher," London, 1871, p. 473.
[20] "Diamond Fields of Southern Africa," pp. 295–296.

ways found to be composed entirely of the coarse material, the finer particles having all been blown away. This process of natural concentration proceeds continuously, the percentage of coarse particles being hereby steadily increased while the sand goes to swell the vast volume of the dunes. As a result of the same action the diamonds scattered through the sand and gravel slowly find their way to the surface of the deposit and into the crests of the waves, where a considerable enrichment is invariably found to have taken place. In the Pomona area, and particularly in the celebrated Ida Tal, this concentration has proceeded to such an extent, that not only the sand but most of the larger particles have been swept away and there remains in place but a single layer of comparatively coarse and fabulously rich detritus, spread irregularly over the wind-scoured surface of the underlying limestones.

Apart from the superficial enrichment one frequently finds a considerable concentration of diamonds to have taken place on the windward side of obstacles, such as the outcrops of the resistant dykes and quartz veins, which rise above the general level of the deposit; and also at the head of the valleys facing the direction of the wind.

Prof. Scheibe states that near Luderitz the average content of diamonds was originally from three to five small diamonds per cubic meter, but that where wind concentration had occurred, the grade, through the removal of the lighter material, had been raised eight or ten times. That even the diamond may be wind-worn is shown by this further quotation from Wagner:[21]

In consequence of the violent attrition to which they have been subjected many of the crystals show unmistakable signs of wear.

Some garnets in New Mexico and Arizona have smoothed and even highly polished facets through wind erosion. Regarding this region H. E. Gregory[22] says:

At Garnet Ridge (Arizona) wide expanses of bare rock are exposed and strong winds and storm-fed sheets of water keep the surface swept clean of fine materials. The garnets are, therefore, plainly in view, strewn over the surface or accumulated in pockets and riffles. The great quantity of garnets and the ease with which they may be obtained give this area first rank as a collecting field. In selected localities, five minutes is sufficient time for gathering from a natural riffle a quart of material of which fully one-half is garnets.

[21] *Idem*, p. 297.

[22] ECON. GEOL., vol. XI., 1916, p. 226.

From two anthills he obtained a bushel of mineral fragments, 40 per cent. of which were garnets.

In Kashmir, sapphires were formerly obtained in quantity from the boulders of a talus, although hard granite was in one instance mined. Gems occur in glacial deposits in small quantities. Countries covered by ice in the Glacial Period are poor in gems, since not only are glacial deposits poorly classified, but in addition, the weathered and cheaply minable rocks have been planed off by glacial erosion.

Precious Stones Deposited by Water.—Opals have been formed by waters given off by cooling acid lavas, and agate and amethyst by those of basic lavas. No gems are formed by the process of secondary enrichment so important in ore deposits. Of precious stones, but one of importance—turquoise—is formed by descending surface waters. Turquoise, in commercial quantities at least, is largely confined to the upper 100 feet of the earth's crust.

Some chrysoprase originated during the serpentinization of the country rock and its veins in instances may pinch out at moderate depths. In the Hungarian opal mines and in certain of those of Australia, it is stated that with depth the gem content decreases. It is doubtful whether the mines have reached a depth to warrant such a generalization, although from the origin of the mineral itself, it is altogether improbable that opal extends to great depth.

ALTERATION OF PRECIOUS STONES.

Surface waters may enhance the value of precious stones or detract therefrom. W. G. Bleeck[23] states that some of the Burmese jadeite, occurring as boulders in laterite, is stained red along cracks. Such staining greatly increases the value of the stone in the eyes of the Chinese, since the artist cleverly utilizes such markings, for example, as midribs of leaves. Bone turquoise owes its value wholly to staining by surface waters, but the color is readily bleached, spoiling the gem.

The unreliability of the color of turquoise is proverbial. A. Hontun Schindler[24] states that the turquoise from the Reish mine,

[23] *Rec. Geol. Sur. of India,* vol. XXXV., part IV., pp. 254–285, 1907.

[24] *Rec. Geol. Sur. of India,* vol. 17, 1884, pp. 132–142.

one of the Persian Nishapur group of mines, fades and becomes "dirty green with white and gray spots. As long as these turquoise are kept damp, they preserve their color; if once they get dry, they are worth very little." In consequence the stones from the Angiri mine, which also fade, are sent to Europe in earthenware pots in which they are kept until they are sold. Other writers say that in order to retard the discoloration of the stones, the local merchants keep the gems in their mouths until they are ready to display them; the buyers on the other hand attempt to possess the stones sufficiently long, prior to bidding for them, to determine whether the color will or will not deteriorate. Amazonstone obtained from shallow depths is not infrequently stained by limonite particularly along its cracks. It is said that such blemishes can be removed by careful treatment with oxalic acid.

According to Fritz Noetling,[25] the amber of Burma occurs in Lower Miocene clays which are normally of blue color, but which weather brown. During this process of oxidation the amber loses its color and becomes dull and brittle.

A number of precious stones have their colors bleached or altered by exposure to light. Topaz, rose quartz, amazonstone, carnelian, zircon, chrysoprase, fluorspar, tourmaline, amber, amethyst, kunzite and pink beryl are examples. In certain Colombian emerald localities, the stones at the surface are pale in comparison to the stones obtained at greater depth. Duparc[26] believes that the pale salmon color of certain beryls from the pegmatites of Antisirabe, Madagascar is the first stage in the alteration of peach-bloom pink beryls. G. F. Kunz[27] states that near the surface, California kunzite is colorless or pale rose, the rich lilac-colored stones occurring only at depth.

The carnelians of India, when first weathered from the basic lavas, are said to have in many instances a greenish tone, which after long exposure to the sun's rays changes to a beautiful red. Here evidently the ferrous iron is in part at least changed to

[25] *Rec. Geol. Sur. of India,* vol. 25, 1892, part III., pages 130 to 135; also *Rec. Geol. Sur. of India,* vol. 26, pages 31 to 40.

[26] *Bul. Soc. Franc. de Min.,* vol. 33, 1910, pp. 53–67.

[27] *Amer. Jour. Sc.,* ser. 4, vol. 16, p. 264.

ferric iron. Clarence C. Sample[28] in describing the amber of Santo Domingo, which occurs as nodules in sandstone, states "The color of the amber varies from light yellow to deep red and even black. The red amber can be bleached by a few hours' exposure to the sun. The surface cracks and a yellow brittle film forms around the amber which when scraped off leaves the inner portion light yellow. The black amber cannot be bleached; it is worthless." To quote H. L. Bowman[29] concerning the pink tourmaline from Haddam, Conn., "Mr. Spencer informs me (Jan., 1902) that the pink specimens in the British Museum have faded very markedly during 4 years exposure in a glass case."

The topaz, however, furnishes the classic example of such color changes. N. von Kokscharow[30] was perhaps the first to observe this change; in a month's exposure to daylight a Trans-Baikal wine-yellow topaz was bleached: a second honey-yellow topaz lost its color in three or four months and a third topaz changed in a year from dark wine-yellow to bluish white. H. B. Patton[31] in describing gem topaz occurring in lithophysæ in rhyolite of the Thomas Range, Utah, writes:

> As already mentioned by A. H. Jones, the topaz crystals of this locality are all originally of a wine color, which color fades on exposure to the sunlight. It invariably happens, therefore, that all the crystals found on the surface are perfectly colorless and all have a wine color when found in a freshly opened cavity. . . . It is unfortunate that the color, as is so often the case with topaz, is not permanent. The color disappears quickly with very gentle heating. After exposure to bright sunlight for thirty hours, a marked fading of the color was to be noticed. After forty-eight hours' exposure to direct sunlight, the smaller and lighter colored crystals lose their color, and after about seventy hours the deeper colored ones become nearly colorless.

Whitman Cross[32] says regarding the topaz found in the cavities in rhyolite at Nathrop, Colo., "it was noted that nearly all of

[28] *Eng. and Min. Jour.*, vol. 80, 1905, p. 250.
[29] *Min. Mag.*, XII., 1902, p. 108.
[30] "Materialen zur Mineralog. Russland," vol. 4, p. 34, 1862.
[31] *Bulletin of the Geol. Soc. of Am.*, vol. 19, p. 184.
[32] *Amer. Jour. Sci.*, ser. 3, vol. 31, pages 432 to 438.

them obtained from open cavities were colorless or of a pale bluish tint while those found in breaking open solid masses were most frequently wine-colored." Because of this feature, the better crystals of topaz in many museums are protected from strong light.

Precious stones as a rule are notably resistant to weathering. Rubies, however, may weather to diaspore, garnets to iron-stained clayey products and a lenticular central portion of a tourmaline crystal alone may be of value for gem purposes, or the stone may completely disappear. Spodumene and cordierite alter readily and are found in nature usually to have an altered exterior. There are no secondary forms of diamonds except perhaps cliftonite, which occurs in meteorites in Youndegin, Australia. This appears to be a pseudomorph after diamond, indicating that, at some period in the history of meteorite, the temperature was greater than 3,600° C., at which temperature diamond changes to graphite.

It is possible that a quantitative expression of the rate of weathering of certain minerals might be obtained from a comparative study of ancient cut gems. The length of time during which weathering has been in force as well as the exact conditions of weathering are in many instances known. The highest polish becomes dimmed in time, the result being compared by Dr. C. W. King in the case of an intaglio to that produced "by breathing upon the original high luster." Jades buried in Chinese tombs of the early dynasties have been softened to a steatite-like substance and in addition are discolored by rust. The exterior of ancient amber ornaments found in the burial places of Europe through oxidation has become darker in color, less transparent and brittle.

ROCK WEATHERING IN RELATION TO GEM MINING.

Rock weathering is important in gem mining, largely because it lessens mining costs, although there is also brought about an actual concentration of stones. The latter may result from abstraction by water of the more soluble constituents of the gem-

bearing rock or by the removal of its lighter constituents by wind. The diamond-bearing kimberlite pipes of South Africa illustrate both enriching processes. The thoroughly weathered "yellow ground" is a clayey substance readily milled and the "blue earth" below this when spread upon the surface of the so-called "farms" disintegrates in a season or two. The deeper "blue earth" however is much more resistant and in 1920 the DeBeers Consolidated Mines, Limited, following in the footsteps of the Premier Diamond Mining Company, Limited, installed direct treatment, crushing the kimberlite as received from the mine. The "yellow ground" of South African mines contained in instances six or seven times the diamond content of the unweathered pipe rock. Thus the Premier Mining Company in the first year of its operation (1902–3) treated "yellow ground" which contained 1.29 carats per load, while by 1920–1, the grade had fallen to 0.176 carats per load. "Farming" of the basic rock containing sapphires is practiced in Montana.

The importance of weathering in gem mining is shown by the almost total absence of gem deposits in glaciated regions. Weathering is particularly important in mining of precious stones which occur in pegmatites, for such ore shoots are notably erratic and a slight increase in grade or a small decrease in mining costs may determine whether operations are carried on at a profit or at a loss. Not alone is the gem content of many pegmatites of insufficient value to cover the cost of hard rock mining, but blasting injures the brittle gems, and for this reason where explosives are necessary, black powder is used instead of dynamite to decrease the jar. The stones from the weathered zone may be somewhat altered, and in consequence of less value, but only in the case of the semi-precious varieties of feldspar (amazonstone, etc.), fresh pegmatite must necessarily be mined. Gems in weathered material may be more flawed than those found in depth, but in extracting the crystals from fresh rocks, in most instances at least, an equal number of flaws is produced. Usually in pegmatite mining, the weathered zone alone is mined, as for example, in the tourmaline mines of Madagascar and Maine. The

beautiful rose tourmaline, so effectively used in Chinese jewelry, is obtained from Burmese quarries in the weathered parts of pegmatite dikes and from their residual soil. In both Brazil and Madagascar, beryl has been concentrated in the surficial portions of pegmatite, largely through the removal of feldspar. In Brazil, diamonds have been recovered at several localities from sandstone, but mining ceases to be profitable when the soft weathered rock is penetrated. Certain of the opal deposits of New South Wales are said to be profitable only to the depth to which the rock has been softened by weathering. The Emmaville (New South Wales) emerald locality became unprofitable when the fresh rock was penetrated.

In the Burma ruby mines, C. P. Brown and J. W. Judd report that the earth in the tortuous tunnels dissolved out of the ruby-bearing limestone has afforded some magnificent gems.

RESUME.

Diamonds make up about 94.3 per cent. of the value of the world's production of precious stones. Because South Africa is a diamond-rich petrographic province, the African continent produces about 92.5 per cent. of the world's precious stones. The importance of kimberlite as a diamond producer makes basic igneous intrusive rocks the premier geologic source of precious stones, followed successively by stream gravels, fossil matter, pegmatites and descending water deposits. Due to mechanical concentration, gravels derived from rocks containing a small fraction of one per cent. of precious stones are frequently exploitable. Precious stones from gravels are of higher quality than those obtained by rock mining. Soda-lithia pegmatites are the source of a wide variety of gems. Rock weathering results in lessened mining costs and a slight enrichment, permitting exploitation in the weathered zone of rocks which at depth are unprofitable. Precious stones, although relatively stable minerals, are, in instances, altered by surface waters or by bleaching.

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ORIGIN OF THE BILBAO, ALMERIA, AND SANTANDER IRON ORES.

R. W. VAN DER VEEN.

European geologists consider the origin of these ores to be hydrothermal. In the second edition of "Mineral Deposits"[1] Lindgren mentions the belief of Adams that they are formed by downward percolating solutions. Therefore it may be of some interest to American geologists to discuss them in the light ot recent developments.

GEOLOGY OF THE REGION.

Detailed descriptions of the geology are found in the references listed below,[2] a brief summary of which is here given. The province of Vizcaya is built up of Cretaceous rocks. The oldest belong to the Urgo-aptien (gault) and consist of micaceous sandstones, upon which rest coral limestones. Then follows Cenoman (Upper Cretaceous) with calcareous sandstones, shales and marls. Tertiary diabase-eruptives occur throughout the whole northern mountain ridges of Spain, nearly all of small size. In Monte Axpe, half a mile northeast of the ore region, is found a trachyte next to a diabase outcrop.

These strata are folded in a northeast direction and show in this province two single folds, the oldest sandstones occurring in the anticlines as mountain ridges, of which the southwest is the most important for the ore formation. The direction of the axes is northwest-southeast. The sandstones range in composition from real sandstones to psammitic and calcareous sandstones.

[1] McGraw-Hill & Co., New York, 1919.

[2] D. Ramon de Yarza, "Descripcion física y geológica de la provincia de Vizcaya," 1892.

John, Glückauf, pp. 2002–2045.

Beyschlag-Krusch-Vogt, "Die Lagerstätten der nutzbaren Mineralien und Gesteine," II., pp. 320–328.

Iron resources of the world, geological map, 1910.

On this anticline and along the sides dipping under the Cenoman rocks remain islands of limestone, and in these remnants, spared by erosion, the bulk of the ore is found. Sometimes mineralization extends into the underlying sandstones and has a vein-like character. Mining has not been extensive in these veins and has not gone deep, so that it is not yet proved that they are of hydrothermal origin.

ORES.

The primary ore is iron carbonate. Up to the present almost all the mining has been done in the oxidized parts of the ore bodies, which, lying almost at the surface, were easily accessible. Alteration has first led to the forming of the so-called "campanil" and "vena," then to a final product, the "rubio."

Campanil and vena are names for the red, hard or earthy hematite, in many parts pseudomorphous after iron carbonate, showing almost the same structure as the carbonates. The rubio is nearest the surface and of very porous and cavernous structure, showing limonite in stalactitic and drusy forms. This ore proves to be the result of removed and redeposited iron oxides in the upper part of the ore bodies.

Erosion has produced here and there eluvial and alluvial deposits. The eluvial ore occurs sometimes as a recent ore breccia of rubio, sometimes as loose chert (chirta) in residual clay. Alluvial chert is led down in the valleys, showing the same structure and composition as the rubio.

Average analyses of the different ore types are as follows:

	Carbonates.	Campanil.	Vena.	Rubio.
Fe.....	38–41	52.70	56.80	51.—
P.....	0.018	0.010	0.015	0.024
S.....	0.20	0.014	0.016	0.040
Mn.....	0.7	1.03	0.65	0.37
SiO_2.....	6.5–9.—	5.3	6.2	9.7

The ore bodies form irregular masses, sometimes of considerable size in the limestones, sometimes of a more vein-like shape. The roof of the ore is mostly formed by the Cenoman shales.

The two most important masses mined to date lie in the Somorostro district at Trianon and Matamoros, of 7,000 by 3,000 feet and 10,000 by 400–3,000 feet, respectively, for the surficial dimensions. The thickness of the bodies varies between 130 and 33 feet. Adan de Yarza estimates that the amount of hematite ore in these two masses alone has been 160,000,000 tons.

FAULTS.

Two systems of faults are noted. The oldest is more or less perpendicular to the anticline axes, the direction varying between north and northeast. It is intersected and displaced by the second system, which runs parallel to the folds and the strike of the strata. These faults are very regular over long distances and are parallel.

Throughout the whole region a great number of thermal springs issue near the intersection of the two fault systems. The diabase eruptions are more or less arranged along the later fracture lines.

In the ore region, occupying an area of 7 by 30 kilometers, the miners have long recognized the fact that the ore bodies occur along the lines of fracture parallel to the anticline axes. The more vein-like ore bodies all strike in the same direction.

During the last few years, a more detailed and scientific investigation in some districts has shown that most ore bodies occur at, or nearly at, the intersections of the two fault systems. This knowledge gives a proper method for exploration. With a knowledge of the exact position of the faults in a district, drilling may be done near the intersections. Investigation has shown also that the ore bodies continue, and additional ones occur in the limestone at considerable depth, where it is covered by younger strata.

GENESIS OF THE ORE.

Observation shows that the ore bodies have some connection with the faults and occur generally in the limestone.

The conclusion is justified that the ore was formed by solutions which moved along the lines of fracture and was deposited in the limestone by replacement.

We may ask next: (*a*) What was the composition of the solutions? (*b*) Whence did they come?

(*a*) The ore of the deepest levels is iron carbonate. The vein-like bodies in the sandstones are also of iron carbonate. The solutions must have carried dissolved iron carbonate, most probably by an excess of CO_2. Diminishing pressure and temperature caused CO_2 to escape and some carbonate was dropped in the sandstones. In the limestones the carbon-dioxide solutions acted on the rock, leaving the less soluble $FeCO_3$ in the place of the more soluble $CaCO_3$.

(*b*) The main question remains: were the solutions descending or ascending? In other words: are the siderite bodies formed by downward percolating solutions from weathering overlying calcareous shales, or are they deposited by magmatic waters?

During my visits to the district I became convinced of the evidence of hydrothermal action by the many facts I will try to set forth here, discussing in the meantime the other different views.

Weddings believed that many warm iron-containing juvenile sources formed a big lake in this place. At considerable depth the lake bottom was changed into iron carbonates. When the lake cooled down and CO_2 escaped, hematite and limonite were deposited on these carbonates. The hematite pseudomorphous after iron carbonate is against this theory. As the weathering of the carbonate to campanil and rubio is proved by this pseudomorphism, no more complication is necessary.

The oxidized ores and carbonates beneath the overlying concordant Cenoman strata is another fact difficult to explain by the lake theory. The irregular metallization of the limestone, where it should have been equally exposed to the lake water, and the lack of any sedimentary iron ore on the bottom, are both facts against it.

Adams' theory of rock decay and weathering has, for all who are not familiar with the district, a much greater attraction.

We are convinced now that the origin of an ore formation cannot be determined by physico-chemical tests alone, nor by mere

mineralogical or microscopical investigation and contemplation, but that the answer to almost all problems of ore genesis lies, ultimately, in the field. The physiographical and geological features of the area concerned are, up to the present, the highest court in economic geology.

Considering the geology of the region, we cannot find, in this relatively small area, a source in the overlying strata from which the enormous quantities of iron, concentrated as carbonate, could have come.

First: These shales, as far as they remain adjacent to the ore bodies, do not show a content in iron sufficient to justify this supposition, nor do they show any weathering pointing in this direction. Other rocks more ferruginous do not occur, except the eruptives. In the whole region no formation younger than the Cretaceous exists.

Second: Would weathering of calcareous shales with a small iron content produce siderite? Everywhere in this region and also in the nearby province of Santander, we find oxides as a result of iron concentration by rock decay and weathering.

Conditions under which this concentration of siderite might have been caused by rock decay would be very exceptional. In this case we would have to postulate a reducing atmosphere and large quantities of CO_2 in the groundwater. Moreover, it is difficult to believe that the groundwater would not have dropped part of its iron as oxides in the upper oxidation zone. Here there is no sign of the slightest residual deposit.

The weathering hypothesis would require not only the presence of an iron-bearing rock, now absent, but also exceptional atmospheric, stratigraphic, and tectonic conditions, which we cannot discover in the district.

But we have still more positive arguments against it: the structure of the ore and ore bodies.

The action of groundwater on limestone forms irregular cavities of varying shape. In the Bilbao region we see this recent action very clearly and in the underground workings these cavities, filled with water and mud (residual clay), are a great

nuisance to the miners. The form of the ore bodies deposited by cold solutions in limestone would have been that of filled caves and openings. The ore bodies in Bilbao are different, as we shall see later. The action on the limestone of iron-bearing groundwater, derived from the weathering of the existing ore bodies, can be studied in perfect detail; and we see here, as everywhere else, deposition and replacement in ferric form. Some small vein-like ore bodies in the limestone are good examples. In the upper levels, near the surface, the body of oxides is of considerable thickness. It becomes gradually thinner towards the deeper primary carbonate zone.

There is a marked difference between the boundary of limestone and ore in the two zones. The rubio ore is sharply separated from the limestone and almost always some residual clay is between rock and ore, so that it can be mined easily. When the ore is mined, the wall of limestone with its irregular eroded surface looks like a cave. Sometimes the many fossils in it are separated out on the surface in "bas relief." The carbonate zone, on the contrary, does not show any sharp contact with the limestone, but grades gradually into it. The ordinary limestone is compact, fossiliferous, and amorphous. The siderite has a coarse crystalline texture; fossils and original structure have disappeared. Replacement has spread like oil through the rock, producing different zones of mineralization around the water channels. Here we see the stages of replacement, from coarse crystalline siderite towards coarse or finer-grained ankerite, fine-grained dolomite grading into the common limestone.

This structure must be the result of warm solutions under pressure. The waters must have penetrated far beyond the walls of the main fissures into the compact limestone, and only pressure and heat can have made this penetration possible.

The Process of Diffusion in Metasomatism.—In the process of mineral genesis out of watery solutions a great deal of the transport of the chemical compounds necessary for the deposition is supposed to be done by the movement of the solutions themselves. As long as the fissures through which the waters move are of

super-capillary size, this may be true. In replacement action, however, the openings of the rocks, soaked with the solutions, are almost microscopical pores and other capillary and sub-capillary openings. The constant supply of fresh material to be deposited, as well as the removal of the dissolved rock components backward and forward, cannot be sufficiently explained by the moving of the solutions alone, but a great deal is probably to be accounted for by diffusion. Heretofore the action of diffusion in geology has not been given much consideration, although Liesegang has called attention to its probable importance in geology. In slowly moving or stagnant waters, for instance, its rôle must be of importance.

The gradual transformation of limestone to the crystalline products of limestone, dolomite, ankerite, and siderite, can be explained fully by this process. On the contrary, with the hypothesis of circulation of the solutions only, we cannot well explain how, for instance, the dissolved calcium carbonate is removed. As a matter of fact, the solutions, once having penetrated in lateral direction into the wall rock, will not have an easy outlet.

In the case here discussed, the solutions bearing iron and carbon dioxide in excess penetrate the limestone. The front line of the attacking army will drop its iron soldiers in the captured trenches and diffusion will supply new troops from behind to restore the lost equilibrium of the density in the front line. The captured calcium is carried to the rear by the same force. In the front line there will, of course, soon be formed a saturated solution of calcium carbonate in an excess of CO_2. The amorphous limestone will be attacked first by this CO_2 as a result of the higher temperature of the solutions, and under these new circumstances it will recrystallize. When this effects some reduction of volume, perhaps some calcite will deposit out of the solution. In front the concentration of the calcium carbonate will always be near the saturation point; toward the rear the concentration will progressively decrease. Therefore it will travel towards the main fissures, in a direction opposite to the direction of travel of the iron ions. There will be thus an exchange of

iron and calcium between the solutions moving in the broader channels and the nearly stagnant water in the wall rock. A similar exchange, caused by the same action, is to be observed in the endomorphic and exomorphic contact zones of eruptive rocks.

Returning to our subject, we have still to consider the magnesium. When a small amount of magnesium carbonate is present in the limestone, this will be replaced also by the less soluble iron carbonate, though not so readily as the more soluble lime. Diffusion tends to spread it in all directions. But in the front is the recrystallizing limestone, which is more soluble than dolomite, so that it will be replaced partly by magnesium. Diffusion will also carry back some magnesium, but the requirement for this element will be greater in front, because it will drop out to take the place of the calcium, whereas in the rear nothing remains to be replaced. The result will be that most of the magnesium is driven along ahead of the conquering iron troops and their gas attack.

The formation of the dolomite, which is so often found around metasomatic deposits of iron, lead, and zinc, is generally a result of a redeposition of magnesium carbonate already present in the limestone and not of the introduction of a new substance brought by the attacking solutions. The different zones in contact metamorphic deposits, the rhythmic precipitation in these and other ore formations, can be explained in this light, considering also the different speed of diffusion for different ions. In the intermediate zones of the iron deposits, Ca, Mg, and Fe will combine to form ankerite and other intermediate minerals. Perhaps diffusion is accelerated by difference in electric charges of the penetrating solutions and the attacked rock, acting in the same way as electro-osmosis. Once demonstrated that the ore is formed by warm solutions under pressure, the possibility of formation by downward percolating solutions becomes very small.

Let us now examine the whole region of the Cantabrian-Asturian coast range.[3]

[3] See map, p. 827, in "Ore Deposits," by Beyschlag, Vogt and Krusch, vol. 2, Macmillan & Co., 1916.

Beginning from the east are, first, the Bilbao ores. Toward the west zinc ores begin to occur, in Reocin, Udias, Andara, Picos de Europa and in other places, gradually losing the iron as companion. In Asturias we find the quicksilver deposits of Mieres. The connection between these different mineralizations is interesting. In Vizcaya, younger veinlets of galena, zincblende and pyrite occur in the iron ore bodies; in Santander the iron ores gradually give way to metasomatic zinc ores; in Andara and the Picos the zinc sulphides show traces of cinnabar. The cinnabar becomes more important in the west, and in Mieres it forms the only important mineral, occurring together with realgar and auripigment. Small eruptive manifestations show themselves throughout the whole range. We are forced to recognize the unity of all these geological features: folding, fracturing, diabase, and trachite eruptions, ore formation and springs along the lines of fracture.

The whole geological history of the district is thrown in the balance for the hydrothermal origin of the iron ores. The last living offsprings of volcanic activity with their feeble murmuring sounds claim their relationship with the metallogeny of the province.

During and after the ore formation, tectonical movements continued. In the hematite ore we find along the lines of fracture polished surfaces, showing that even after the oxidation of the ore, movement went on.

Also in the carbonates are veins of ankerite with breccia of siderite. In some cases the throw of the faults is so great that the ore on both sides of the fault is no longer in contact.

ADJACENT IRON ORE DEPOSITS.

A short description of two other iron districts in Spain is here given, because in one case are found iron ores of the same replacement type, doubtless formed by volcanic phenomena, and in the other, a district near Bilbao, are found iron ores which have been formed by rock decay and weathering with a result totally different from the ores of Bilbao.

Iron Ores of the Province of Almeria.—The mountain ridges in this province, belonging to the Betic system or Alpine folding, are apparently single folds, of which the Sierra Nevada is the main ridge. Towards the east this ridge is succeeded by two ridges, the Sierra Alhamilla and Sierra de Filabres. They are composed of crystalline (perhaps Archean) schists, upon which crystalline micaceous limestones rest like islands spared by the erosion. On these limestones, or, in their absence, on the schists, lies a basal conglomerate and overlying Trias beds. The succession of the strata from the youngest to the oldest is as follows:

Recent conglomerate Limestone and dolomites Blue shales Basal conglomerate	Triassic
Cipoline marbles Mica-schists	Archean

Pliocene and Pleistocene deposits occur in the valley of the Almanzora. To the south of these mountains lie the big, eruptive stocks of Cabo de Gata. In the Archean limestones (Sierra Nevada and Sierra de Filabres) and, where these are absent, in the Triassic dolomites (Sierra Alhamilla) are iron ores, some of considerable value. Ores occur in the following localities:

In the eastern part of the Sierra Nevada the most important deposits are Coto de Beires (6,000 feet above sea level) and Alquife. In the Sierra de Filabres: Coto San Miguel y Dulce Maria (5,000 feet) and Coto de Bacares and Menas. In the Sierra de Alhamilla: a small deposit in the southwestern part of the Sierra, where in the same deposit issues a warm spring of 59 degrees Celsius, and a more important deposit, now mined out in the northeastern part, where also warm medicinal springs occur.

In the *Sierra de Filabres,* the ore bodies are distributed along faults, as are the diabase and ophitic eruptions, which are found in great quantity throughout the whole region. The character of the ore is the same as that of the Bilbao ores, but here the

limestone was crystalline before mineralization took place and the structure as a whole has been preserved. A freshly exposed face of carbonate ore, therefore, has much the same appearance as the unaltered beds of limestone. In addition the mica from the limestone has remained unaltered, even during the oxidation which followed, and the red hematite is full of small glittering mica particles.

The average analyses of the (oxide) ore are: Fe, 50 per cent.; SiO_2, 6.2 per cent.; S, .01 per cent.; P, .009 per cent.; Ca, 2.1 per cent.; Mn, 1.65 per cent.; H_2O, 4.53 per cent.

In the western part of the ridge, the Sierra de Baza, are a number of siderite veins in the crystalline schists. They have been worked in two districts, Tesorero and Gergal, in the latter to a depth of 600–800 feet. The veins are nearly vertical and show the hydrothermal character of the ores in this region. They represent the deeper channels through which the waters ascended.

The ores from these veins contain a small amount of copper. In Tesorero it has been found that the copper belongs to a later period and chalcopyrite has replaced the siderite. Bismutite in small needles also has been introduced later. In the whole region small quantities of copper, lead and zinc, and quicksilver are found. The analogy with the Bilbao mineralization is striking.

The ore of *Coto de Beires* is analogous to that of the San Miguel region. Here there are later tectonic movements of the formations. They have consisted, for the most part, in slips along the slopes of the mountains, where the original situation of the limestone was much higher. The result is that in climbing the mountain one sees the ore bodies several times repeated, a situation which would readily mislead the inexperienced.

In the *Sierra Alhamilla* the Lucænena Mine is the most important. Here the mineralization is in the Triassic dolomite, where it forms one flank of an overturned anticline and dips almost vertically. The mine has been worked to a depth of 1,800 feet. In the upper parts the ores consist of hematite and considerable amounts of manganese oxides, gradually changing into

siderite below water level. The mineralization has spread here because of the vertical position of the limestone, like shoots in a vein. Strong exhalations of CO_2 make strong ventilation necessary, also the temperature in the workings at greater depth becomes high, as is the case in the workings of the Alhamilla Mine. Here also specularite occurs with siderite, as it does in the ores of Eisenerz, in Austria. The texture of the ore is coarsely crystalline, of the dolomite, crypto-crystalline.

Iron Ores of the Province of Santander.—The ore is loose chert (chirta) embedded in residual red clay, on the eroded surface of dolomitic limestone of Cretaceous age.

The formation of the ore has been studied in the different workings in detail by Mr. J. H. Steggenwentz. In his report[4] he expresses the same opinion of the origin of the ores that I reached in former visits. His conclusions is that "The ores are residual, formed by continental concentration."

The structure of the chert is mostly concretional. All states of concentration in concretions are found, from the beginning of concentration in clay, poor in iron, to sizes varying from that of a small bean to that of an egg. Their form varies from irregular to exactly spherical, like bauxite concretions. Their surface is usually well polished. This is not the result of transportation, because concave surfaces also are brilliantly smooth. The chert formed in the clay has concentric structure. Where the resistance in the soft mass has been equal in all directions, true spheres are formed; where this was not equal because of other resistances or sliding, which are frequent in the almost heterogenous clay, more irregular shapes are formed. In this deposit, however, most concretions are formed in the weathering dolomite itself, almost directly at its surface, in holes, cracks, and fissures. Their shape is then irregularly drusical, sometimes with radial structure (see Fig. 57), or as cubes pseudomorphous after pyrite, which must have been formed in the deeper zone of weathering. As decay proceeds, these druses become loosened, and remain surrounded by clay, and later grow in a different way. Gradu-

[4] Jaarboek 1919–1920 van de Mynbouwkundige Vereeniging te Delft.

ally they lose their edges, becoming rounded and covered by later layers of limonite and clayey-iron hydroxides.

Diffusion again must play the principal part in this process. It matters not whether the iron is present in solution or colloidal suspension. When the metastable point of supersaturation is reached, or when in the unstable colloidal solution precipitation or coagulation begins, the superfluous material is dropped at some points as the so-called "amorphous" limonite. These points will form the first crystal germs around which the solutions will be only saturated. Beyond this zone, supersaturation will still reign

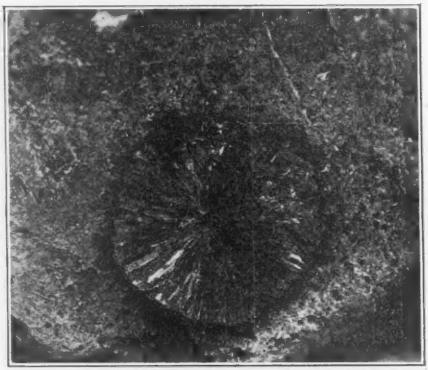

FIG. 57. Chert concretion in dolomite, showing radial structure.

and diffusion will press new material into it. In contact with the germs, supersaturation cannot exist, so that deposition will proceed.

In the clay, diffusion will act very slowly, because of the presence of the colloidal clay itself and its adsorbing power. Throughout the whole clay body iron hydroxides will eventually be held, perhaps largely in jelly form, together with the beginning centers of concretion. Now it is stated that iron adsorbed in the soil is driven out by solutions of $MgCO_3$ and $CaCO_3$; also that the CO_2 and SO_3 in the groundwater and the reducing influence of organic matter in the soil will continually bring some of the present iron

into molecular or colloidal solution again, so that solution and redeposition will be continuous. The result will be the growing of the points where the biggest crystal germs have formed. The change of the seasons will bring another cycle of solution in the rainy time and deposition in the dry weather.

When this process goes on in the clay, where resistance may be equal in all directions, a small globule is formed and diffusion acts in the form of a globe. In the limestone, at the wall of small open fissures, perhaps partly filled with clay, more irregular druses will develop.

The iron oölites developed in the clay are built by concentric layers. Between the layers of limonite in different states of hydration rings of clay still remain, ranging from microscopical to macroscopical dimensions. The concretions in the dolomite do not show this pisolitic structure.

Considering first the oölites, we remember that we do find similar forms in numerous iron deposits of residual origin throughout the world. Also we meet them in the bog ores of iron, in lateritic iron deposits, and in sedimentary manganese ores. An analogous formation is seen in the "rogenstein" of Northern Germany. Here the material is lime carbonate, alternating with layers of clay, so thin that in 1.5 millimeters occur 170 shales, each shale having the thickness of 10μ.[5] The "sprudelstein" of Karlsbad is composed of similar globules. Also we find the same, though smaller, formation in the oölitic iron ores of Clinton, Lotharingen and Luxembourg, the chamosite and thuringite beds of Schmiedefeld. In some of the latter it has been shown that alternating layers of limonite and silica or iron silicates form the oölites.

This rhythmic precipitation is not produced by centripetal diffusion, causing rhythmical zones of supersaturation of a newly-formed substance in jelly matter, as is probably in many instances the case in agate and chalcedony or opal. It is believed by Liesegang[6] that in the case of oölites, the growing is centrifugal,

[5] E. Kalkowsky, *Zeitschrift d. D. Geol. Ges.*, 1906, 68.

[6] *Kolloidzeitschrift*, 1913, p. 74.

and the alternating layers are produced by the successive isolation of the newly-precipitated germs of one substance from solution, by another present in the same solution, which, after deposition of the first, reaches its point of metastable supersaturation. A shale of the second material covers the first layer, making the action of the first crystal germs almost nil, so that again supersaturation can be produced by the ever-acting diffusion. It seems that clay particles can act in the same isolating way.

But still the question remains: why is the spherical form produced? Why are there not produced large individual crystals of zonal structure, such as alums and plagioclases? Why also should pyrite develop in soils almost everywhere in macroscopical crystalline form? Why are barite and gypsum always found in excellent crystals, while limonite, bauxite, phospates of lime, iron silicates, and silica under surface conditions, manganese oxides, malachite, stromatolite, and lime oölites show the formation of rhythmical layers in globes or mammillary forms?

Lindgren suggests the deposition of oölites out of colloidal solutions. I would supplement this statement with the conclusion: When jelly precipitates are formed by some reactions in solutions, under conditions of rhythmical effects, oölites and other shaly-dispersed systems will develop.

The difference between a gel or amorphous-isotropic body and a crystalline precipitate is that the crystals in the first are not readily detectible with optical methods. Even the method of Debye and Scherrer,[7] which examines the finely-powdered substance in monochromatic Röntgen light, shows that a freshly-prepared silica gel[8] is amorphous, although it shows also that one molecule contains several Si-atoms. A dehydrated silica gel showed crystallinity.

P. P. von Weimarn states[9] that the more the concentration of the reacting solutions exceeds the saturation-concentration of the precipitate, the smaller the resultant crystals will be. Gels or

[7] *Physikalische Zeitschrift*, 1916, p. 277.

[8] S. Kyropoulos, *Zeitschrift f. anorganische u. allgemeine Chemie*, p. 197, 1917.

[9] "Zur Lehre von den Zuständen der Materie," 1913.

colloid-amorphous precipitates are formed, when a body formed by reactions of solutions of sufficient concentration is brought into conditions of minimal solubility. Now Fe_2O_3 has an extremely small solubility, so that in superficial and cold solutions it will precipitate almost always as a gel. In the clay as a colloidal medium, the mobility of the molecules will be hindered. Around some particles of other substance the first precipitate will settle. And because of the scalar properties of amorphous bodies the precipitation will form a scale. Theoretically we must accept that the properties of small molecule complexes must be vectorial even as the larger ones. But where a hydro-gel is a two-phase system of a liquid and a solid and where we see that the properties are scalar we may conclude that surface tension of the liquid still dominates the vectorial forces of the solid. Only when the gel loses its water will crystallinity set in.

Once a small scale has formed, supersaturation will slowly diminish and the growth of crystals of macroscopical size out of the ultra-microscopical crystals will be a process involving long time. When other substances are present in the solutions, they will have time enough to form their following isolating layer, also as a scale. Afterwards, perhaps accelerated by dehydration, the different layers become crystalline.

Barite and calcium sulphate for instance are, in comparison to iron oxide, very soluble substances, so that gels would form only by reaction of strong solutions of them, which in nature do not exist. Therefore they develop as crystals.

The concretions in the dolomite are radial, because there was no rhythmical precipitation, due to the absence of the clay particles. A recrystallization produces the radial structure uninterrupted by the different scales as is the case with the oölites, where every layer itself shows a radial crystallization.

The ores are found on the slopes of the Peña de Cabarga, where the clay is held by the pinnacles of the eroded dolomite. When gradually the underlying marls are laid bare by the erosion and thus the pinnacles become shorter and finally disappear, the ore is washed with the clay into the valleys, where it is found in more or less stratified layers.

The analyses made by Steggenwentz of dolomite, clay, and chert are:

	Dolomite.	Residual Clay.	Chert.
$CaCO_3$	58.68	—	—
$MgCO_3$	36.06	—	—
Al_2O_3	1.82	21.97	—
SiO_2	0.76	28.97	4.77
Fe_2O_3	2.68	36.42	55.2

The material is treated very simply by logwashers and the average analyses of the ore delivered are:

H_2O, CO_2	4.35– 8.12	SiO_2	3.54–9.55
Fe_2O_3	55.66–60.7	MnO_2	0.12–0.84
Al_2O_3	0.41– 2.05	CaO	0.20–0.42
S	0.06– 0.17	P	0.01–0.02

The ores are doubtless residual, formed by rock decay and weathering, like the brown hematites of the Appalachian region and of Berry in France and Hessen in Germany. Perhaps former iron ore bodies, similar to those of Bilbao, existed, perhaps a feebler mineralization of the dolomites is responsible.

The ores of Bilbao and of the province of Santander are so different that the same geological actions acting under almost the same geological conditions cannot have led to deposits of such entirely different characters.

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REVIEWS

The Geology of the Corocoro Copper District of Bolivia. By JOSEPH T. SINGEWALD, JR., and E. W. BERRY. The Johns Hopkins University Studies in Geology, No. I. The Johns Hopkins Press, Baltimore. 115 pp. 7 plates. 1922. Price, $1.25.

This constitutes the first of a series of monographs to be issued under the auspices of the Geological Department of Johns Hopkins University. The report is essentially a critically prepared summary of the geological literature dealing with this famous native copper producing district, including in the summary the results obtained by Singewald and Miller which were published in 1917. In addition important new contributions are made as a result of the author's visit to Corocoro in 1919 when a geologic map of the vicinity of the mines was prepared and fossil plants were collected which fix definitely the age of one of the copper-bearing formations. Little new information is presented, however, bearing directly on the mode of formation of the ores. Some of the more salient features of the Corocoro District as brought out in this report are briefly summarized below.

The city of Corocoro in the Department of La Paz, Bolivia, is situated on the western edge of the high plateau of Bolivia at an altitude of about 13,000 feet. The mines are located in the hills immediately surrounding the town. During the Colonial period the deposits were worked by Spaniards mainly for their oxidized ores, and it was not until about 1830 that the native copper and native silver ores began to be utilized. From that date until 1912 native copper concentrates were the main output of the district, about 200,000,000 pounds of copper being produced in the forty-year period from 1873 to 1912. The completion of the Arica-La Paz railroad in 1912 made profitable the shipment of sulphide ores and led to a great increase in the annual production. In 1919 the production was about 9,000,000 lbs. of copper, of which four fifths came from the sulphide ores and less than one fifth from native copper ores. While the production of sulphide ores has temporarily displaced that of the native copper ores because of the higher grade of the former, the greater tonnage of reserves appears to lie in the native copper ores and at some future time they will probably again be the more important type. All of the producing mines are now under the control of two companies, one a Chilean company and the other Anglo-French.

The copper-bearing sediments of Corocoro form two series known respectively as "vetas" and "ramos" which have similar northerly strikes but dip in opposite directions away from a major fault plane, the Corocoro fault, which separates them. The term "vetas," applied to the westerly dipping series, is Spanish for vein and the term "ramos," applied to the easterly dipping series, is Spanish for branch. While originally applied only to the copper-bearing beds, the terms have been extended to include the copper-bearing formations in their entirety. The authors measured in detail sections of both series. The stratigraphic thickness of their section of the Vetas formation is 1,491 meters and includes ten copper-bearing horizons ranging through 1,110 meters of the section. The section does not represent the entire thickness of the formation. Somewhat over half of the section is shales, one fourth is sandstones, and the remaining fourth conglomeratic sandstones and conglomerates. The shales are almost invariably red but enclose no gypsum beds. A large part of the sandstone is also red, but much of it is gray, and the conglomeratic sandstones and conglomerates are nearly all gray. All copper-bearing horizons are in sandstones and are invariably gray as a result of the reducing action of the mineralizing solutions. Most of the sandstones are arkosic from the presence of fragments of volcanic rocks. Plant remains found at several horizons indicate conclusively that the formation is of Pliocene age. They indicate further that at the time the formation was deposited the altitude of the region was lower and the rainfall greater.

The total thickness of the Ramos formation measured was 3,736 meters, but even this large figure does not represent the entire formation. Of the measured thickness about 80 per cent. was shales, nearly 20 per cent. sandstones, and only 0.3 per cent. conglomerates. The rocks are nearly all red, but near the Corocoro fault a few gray sandstone horizons were noted. Gypsum occurs fairly abundantly as beds, impregnations, stringers, and veinlets. Fourteen copper-bearing horizons were noted in shale, four in sandstone, and two in gypsum. No plant remains were found in the formation, but on the basis of the remains of a single mammal described by Huxley it is regarded as late Pliocene or Pleistocene in age. There is no positive evidence as to the relative age of the Vetas and Ramos formations.

The Vetas and Ramos formations are overlain unconformably by the Desaguadero formation, strikingly similar to the Ramos lithologically. This formation is also younger than the Corocoro fault and younger than the copper mineralization. The only evidence of life in the beds is a fossil footprint.

Igneous rocks, while not found in the immediate vicinity of Corocoro, outcrop 15 km. to the west and 20 km. to the north. At the former locality the rock is a rhyolite porphyry whose age relations to the copper-bearing rocks of Corocoro is unknown. At the locality north of Corocoro the igneous rock is a hornblende diorite porphyry which has intruded the sediments of that locality and metamorphosed them slightly. These intrusive rocks are believed by the authors to be, in part at least, younger than the copper-bearing rocks and to have come from the same magmatic source that furnished the mineralizing solutions.

All of the sediments of the Corocoro district are believed to be Continental deposits derived from the rising mountain mass to the west.

The mines of the district extend for about 4 km. along the Corocoro fault, all being located close to the fault plane. Mineralization is confined to certain beds in the Ramos and Vetas formations close to the fault and has also affected the fault plane itself. Ores have been deposited principally in arenaceous and pebbly beds and only in the Ramos occasionally in shales. The copper-bearing horizons range in thickness from an inch up to 25 feet, averaging about 4 feet. Typical native copper ore consists of sandstone irregularly mottled with specks of copper. The microscope shows that the copper is mainly a replacement of the matrix, penetrating the quartz grains only to a very limited extent. The run of mine ores with native copper usually range from 2.5 to 3.5 per cent. of copper. In the early days small and irregularly distributed but rich pockets of native silver were found in the Vetas, but the native copper concentrates now produced with 85 per cent. of copper carry only 6 oz. of silver per ton. Other noteworthy features of the native copper ores are the occasional occurrence of the copper arsenide, domeykite, as nodules from the size of a pea to 3 or 4 inches in diameter and the presence occasionally of hexagonal prisms of native copper pseudomorphous after aragonite. In the Vetas native copper and barite are present rarely as small veins cutting the bedding but never transgressing the limits of the cupriferous horizon in which they are found.

The sulphide ores that form the present main resources of the district occur in the Vetas formation just below the oxidized zone and in depth pass over into native copper ores, the transition taking place at depths of 150 to 200 meters. The principal sulphide is chalcocite, with which is associated domeykite and other arsenic and sulphur compounds of copper in minor amounts; galena is also mentioned. Microscopic examination shows that the chalcocite is in the main a replacement of the matrix of the sandstone. The chalcocite ores are on the average richer than the native copper ores, averaging 7 to 8 per cent. copper.

Near the surface both the native copper and the chalcocite ores have undergone oxidation and the following oxidized minerals have been recognized: malachite, azurite, brochanthite, chrysocolla and cuprite. The important bodies of oxidized ore were long ago worked out.

The authors believe that the relationships established at Corocoro definitely rule out all syngenetic theories of the origin of the deposits. They attribute the mineralization to thermal solutions ascending from an underlying dioritic magma from which the diorite porphyry masses outcropping 20 km. north of Corocoro were offshoots. With respect to the chemistry of ore deposition they favor Steinman's theory of the oxidation of the sulphides in the mineralizing solutions by the ferric oxide of the red sediments and the reaction of the resulting sulphuric acid with the alkaline earths of the impregnated sediments.

The report concludes with sections on the mining and treatment of the ores and with detailed descriptions of the fossil plants collected from the Vetas formation.

Messrs. Singewald and Berry are to be congratulated on the contributions they have made in this and earlier papers to the knowledge of a unique mining district. Upon the foundations laid by them and by earlier observers it should be possible through a moderate amount of further field and laboratory study to arrive at a satisfactory understanding of the chemistry and physics of the ore deposition. To the reviewer the most promising field for further study appears to lie in a detailed study of the mineralogy of the ores by the aid of polished specimens and the reflecting microscope, with a view to determining in particular the relations between the chalcocite ores and the native copper ores and the relations of both of these ore types to oxidation processes. The relative distribution of the chalcocite and native copper ores areally and in depth is also worthy of more detailed study. Some microscopic studies could probably be profitably made on materials from these deposits already available in museum collections in the United States.

Resemblances between the Corocoro deposits and the great native copper deposits of the Lake Superior region have perhaps been unduly emphasized in geologic literature. At Corocoro there is an absence of basic lava flows, although dioritic intrusives outcrop a few miles away. In the Lake Superior district and in the White River district, Alaska, pebbles of copper-bearing amygdaloidal basalt in clastic beds between basaltic flows show that some of the copper was deposited soon after the flows solidified, while the presence of copper veins sharply inclined to the bedding shows that another part of the copper was deposited later. At Corocoro no evidence has been cited that would indicate more than a single period of native copper deposition. At Corocoro copper sulphides and arsenides

are in places very abundant, while in the Lake Superior deposits they are notably rare. It is significant, however, that the same mineral species, chalcocite, domeykite, and possibly others are common to the two regions.

EDSON S. BASTIN.

Study of Underground Electrical Prospecting. By C. SCHLUMBERGER. Gautier-Villars & Co., Paris, 1920. 92 pp. Translated into English by S. F. Kelly, Paris, 1920.

This publication is a distinct addition to the literature dealing with relations between electric phenomena and ores. Its principal merit consists in its clear presentation of certain physical and mathematical relationships to be expected in field practice, illustrated by diagrams. The field observations are also a timely contribution. Chapter I. reviews previous attempts at electric prospecting. Chapter II. treats of the electric conductivity of rocks and minerals. Chapters III. to V. describe the theory of a potential chart and the method of impressing a potential fall upon a given area or portion of the earth, and of mapping the resulting distribution of potential. This is the method chiefly used by Schlumberger. Charts obtained in the field have shown effects caused by faults, effects related to the dip of tilted strata, effects serving to trace a given geologic horizon from place to place, and effects caused by a buried conducting mass such as a lens of pyrite. Chapter VI. describes the method of studying the horizontal form of a conducting body which is exposed at some point—the determination of the vertical extension not being attempted. Chapter VII. deals with the distribution of a current at depth in the earth, Chapter VIII. with induced polarization and Chapter IX. with spontaneous polarization. The latter chapter sets forth experiments and explanations which are to a considerable extent duplications of those published by the undersigned in 1914 in Bull. 509 of the U. S. Geological Survey, "Electric Activity in Ore Deposits"; in fact many predictions made in this bulletin have been verified by Schlumberger.[1] The accelerating action of galena in the oxidation of pyrite is deduced by Schlumberger from his experiments without any reference to Gottschalk and Buehler's papers.[2]

Schlumberger calculates that to furnish electric currents, such as are observed, the pyrite in a gossan would be oxidized at the nominal rate of about 15 metric tons in 1,000 years.

Unfortunately, he is obliged to conclude that electrical prospecting based on spontaneous polarization suffers from two serious objections. First, disseminated pyrite of no commercial importance simulates in its behavior

[1] See also his article in *Compt. rendus, 174,* 477 (1922).

[2] ECON. GEOL., *5,* 28 (1910); *7,* 31 (1912).

a zone of compact ore. Second, a virgin deposit of pyrite may give very slight electric indications, unless close to the surface, as it is not subject to the lively oxidation that generally ensues in deposits which are being worked.

The author also concludes that none of the electric methods can be expected to give certain and precise results, but on account of their adaptability and wide application, they promise much as auxiliary methods both on the surface and at depth and should be tested further.

The appendix mentions some electric prospecting done in Sweden, based on the use of straight wires laid along the ground and mapping of the interspaced equipotential lines.

R. C. WELLS.

Lehrbuch der Mineralogie. By PAUL NIGGLI. 694 pp. 560 figs. in text. Gebrüder Borntraeger, Berlin, 1920.

This book is not concerned, except incidentally, with the specific properties of minerals but treats rather of their more general characters. The author in the preface emphasizes the fact that the sciences of physics, chemistry and geology all contribute to the study of minerals and in turn these sciences are in many cases greatly indebted to mineralogy. These relationships are repeatedly emphasized throughout the book.

The first division of the book is concerned with a discussion of crystals. The attempt has apparently been made to treat this portion of the subject in a strictly philosophical manner with the result that much of needed simplicity has been sacrificed. For instance, the various crystal systems and symmetry classes are discussed primarily in regard to their relations to each other and nowhere in the book is a connected description of any particular system given. Much the same sort of criticism might be offered to the section devoted to the optical properties of minerals, which in turn forms a part of the second section of the book, designated as crystal physics.

The third topic discussed is that of crystal chemistry. This is an interesting and important section in which is given, first a brief systematic chemical classification of minerals, followed by sections on polymorphism, isomorphism, etc., all of which are illustrated by many examples. This section is succeeded by a short discussion of the amorphous mineral substances.

The last section, which includes nearly one third of the book, is a very detailed and excellent discussion of the various phases of the occurrence and association of minerals. To the present writer this section appears to be the most original and important portion of the book

and upon it the value of the book as an addition to mineralogical literature largely depends. The author very aptly says in one of the closing paragraphs of this section: "Each mineral aggregate is the product of physical and chemical causes. From this product we must derive all the circumstances of its formation. In this sense mineralogy is in great part an historical science with all its especial difficulties but also with its peculiar fascination."

A word of warm praise should be added for the consistently admirable illustrations that are used throughout the text and also for the many tabular expositions of mineral relationships that are included.

W. E. FORD.

SOCIETY OF ECONOMIC GEOLOGISTS

This department has been established for the official communications of the Society of Economic Geologists whereby the affairs of the Society such as notices, minutes, titles of papers, elections, etc., may be brought regularly to the attention of its members.

The Society, as previously announced, was represented at the 13th International Geological Congress at Brussels in August, 1922, by Messrs. R. A. F. Penrose, Jr., and H. V. Winchell.

Below is a résumé of the proceedings of the Congress.

BRIEF NOTES ON THE THIRTEENTH INTERNATIONAL GEOLOGICAL CONGRESS, BRUSSELS, BELGIUM, AUGUST, 1922.

By R. A. F. Penrose, Jr.

The meeting of the Thirteenth International Geological Congress was held in Brussels, from August 10th to August 19th. Before and after the meeting, however, numerous geologic excursions throughout Belgium were taken and these proved of great interest.

From August 10th to August 19th the actual reading of papers and the discussion of various topics took place in Brussels. Numerous important papers were read, and the Council appointed committees and formulated rules and regulations to govern the present Congress and to act as a guide for the next Congress. No one subject was selected for a monograph to be presented at the next meeting, such as had been done previously in the monographs on Iron and Coal. In the final session of the Council, at the suggestion of Mr. H. V. Winchell, a Committee was appointed to express the thanks and appreciation of the Congress to the Committee of Organization for the excellent manner in which they had prepared for and managed the Congress.

An invitation was presented by the Spanish geologist, Monsieur Rubio, to hold the next meeting of the International Geological Congress in Spain. This invitation was cordially accepted.

The official language of the Congress was French, though the reading of papers and discussions were permitted in English. During the intervals between the sessions numerous short excursions were taken in regions accessible to Brussels.

Summary of Meetings.

On August 9th, preceding the formal opening of the Congress, the local headquarters were opened in the Palais Mondial; in the evening a reception was held by the Société Belge de Géologie, de Paléontologie et d'Hydrologie. The formal opening ceremonies for the Congress at large were held on August 10th in the Grande Salle des Fêtes du Palais des Académies, where it was honored by the presence of S.M. Albert King of Belgium, who acted as the patron of the Congress. At the morning ceremonies several important speeches were made, especially by Monsieur Moyersoen, Minister of Industry and Works, on behalf of the Belgian Government; by Mr. Adams, President of the former session of the Congress in Toronto; by Mr. Brock, Secretary-General of the same Congress; and by the President of the present Congress, Monsieur Lebacqz, and its Secretary-General, Monsieur Renier.

At 5 o'clock a reception was given by Monsieur and Madame Moyersoen, at their residence in Rue Lambermont, which was largely attended by members of the Congress.

In the evening, Monsieur Argand, by request, opened a public conference on the Tectonics of Asia. This interesting paper was much discussed throughout the whole period of the Congress. Several other important papers on the same subject, in different parts of the world, were read subsequently by other members. Monsieur Argand displayed a tectonic map of Europe and Asia, entitled "The Tectonic Map of Eurasia." Suggestions were made that this remarkable map should be published; no immediate action was taken in this matter, though the suggestion met with general approval.

On August 11th, a meeting of the Council was held in the Palais Mondial followed by business matters and the reading of papers. At 5 o'clock in the afternoon a reception was given by l'Administration Communale de Bruxelles in the halls of l'Hôtel de Ville, which was extremely interesting and enjoyable, for the many ancient treasures in l'Hôtel de Ville were shown to peculiar advantage on this particular occasion.

On August 12th, the whole day was devoted to excursions, the principal of which was an excursion to Spa. A reception was given at Liége by the Société Géologique de Bélgique, including a visit to the celebrated springs of Spa and a dinner at l'Hôtel Continental.

On August 13th, a visit was made to the Musée Royale d'Histoire Naturelle, and in the afternoon a trip was made to the University of Louvain.

On August 14th, the Council met in the morning, followed by the general assembly. The meetings of the various sections were held in the afternoon. In the evening, in the hall of l'Union Coloniale, a meeting was held in which films and explanations were given of the exploitation of sulphur and iron in the United States.

On August 15th, a second visit was made to the Musée Royale d'Histoire Naturelle, and in the afternoon a visit was made to the Musée Colonial at Tervueren.

On August 16th, following a meeting of the Council, the general assembly met at 10 o'clock for the discussion of various matters and for the reading of papers. The rest of the day was devoted to the same purposes. In the evening the official dinner of the Congress was held at the Pavillon de la Laiterie du Bois de la Cambre. Delegates from the different countries made brief speeches, which were of much interest and were received with general applause.

On August 17th, an excursion was made to the Grotto and the neighborhood of Remouchamps, where a reception was given by Monsieur Francotte, former Minister of Industry and Works, Burgomaster of Remouchamps, and by the Administrative Council of the Société de la Grotte. At the same time as this excursion an alternative excursion was taken to the coal districts of Belgium.

On August 18th, a meeting of the Council was held, followed by the general assembly at 10 o'clock, and the meetings of sessions at 2 o'clock. At 5 o'clock a visit was made to l'Institut Solvay de Sociologie.

On August 19th, after a meeting of the Council, the closing meeting of the general assembly was held.

On August 20th, an excursion was taken to the Grottos of Hans and of Rochefort, and ample opportunity was offered to visit the remarkable caves of this region.[1]

The longer excursions which followed the general meeting commenced on August 21st and lasted until September 3d, during which many interesting parts of Belgium were visited.

A description of this meeting, however brief it may be, would be unfinished without an expression of the deepest thanks and sincere appreciation to the officers and members of the Committee of Organization who prepared the details and carried them out with such perfect precision.

[1] Numerous other short trips not mentioned above were taken during the ten days' meeting of the Congress.

Monsieur Jean Lebacqz, the President of the Committee, was active in his efforts and did everything possible as a presiding officer to direct the meetings of the Council and the Congress in a just, dignified and efficient manner.

The Secretary-General, Monsieur Armand Renier, was tireless in his efforts to make the meeting a success, and he thought of everything that would add to the comfort, to the enlightenment and to the enjoyment of the members. His greatest wish seemed to be to make the Brussels meeting as nearly perfect of its kind as could be done, and his success in this desire was freely acknowledged by all the members present.

The other members of the Congress, consisting mostly of well-known Belgian geologists, gave their splendid efforts to the conducting of the excursions, to the details of the meetings of the sessions, and to all other matters which pertained to the enlightenment, the pleasure, and the comfort of the visiting members.

To the Committee of Organization and its various members therefore the whole Congress owes its deepest and most sincere thanks for a meeting of wonderful interest, conducted with admirable efficiency.

Even this brief résumé of the Thirteenth meeting of the International Geological Congress at Brussels would not be complete without a mention of the kindness and hospitality of Mr. Millard K. Shaler, the well-known American geologist living in Brussels, and having charge of the great Congo concession controlled by the Société Internationale Forestière et Minière du Congo. Mr. Shaler did everything possible for the American members of the Congress, as well as for many of the other members. His genial, cordial and always thoughtful advice and assistance will long be remembered by those who had the good fortune to meet him.

September 30, 1922.

Mr. John E. Orchard has been nominated for and accepted the Scholarship in Political and Commercial Geology of the Society. It will be remembered that funds for this scholarship are derived from the sale of "Political and Commercial Geology" by J. E. Spurr. Mr. Orchard will be resident at Columbia University, the subject of his research being "The Economics of Coal."

SCIENTIFIC NOTES AND NEWS[1]

H. G. Ferguson has returned to Washington after completing field work in the Tonopah Quadrangle, Nevada.

Robert Marsh, Jr., has been made manager of the Consolidated Copper Mines at Ely, Nevada. An energetic development of this property is planned.

F. H. Moffitt has returned to Washington from Cordova, Alaska.

H. G. Ferguson, S. H. Cathcart, and Q. D. Singewald have completed field work for the U. S. Geological Survey in Nevada.

J. F. Kemp has been at Ashland, Alabama, assisting J. S. Brown in his work on the graphite deposits of Alabama.

G. F. Loughlin, of the U. S. Geological Survey, has been relieved of all administrative work in order to resume work on the Leadville monograph.

A. W. Ambrose, chief petroleum technologist of the United States Bureau of Mines, has been appointed assistant director of the bureau, to fill the vacancy created by the resignation of E. A. Holbrook, who has accepted the position of dean of the mining school at Pennsylvania State College.

E. C. Andrews is Permanent Secretary of the Australian Society for the Advancement of Science, and is also the Australian representative of the Pan-Pacific Conference.

F. B. Tough, United States supervisor of oil and gas operations on leased public lands, has been appointed Chief Petroleum Technologist of the Bureau of Mines, to succeed A. W. Ambrose.

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice

W. Armstrong Price, lately geologist with the Humphreys Oil Company, at Mexia, Texas, has opened an office in Houston, Texas, for general consulting work in economic geology and the geology of petroleum. He is associated with Charles W. Dabney, chemist and economic geologist, who was until recently President of the University of Cincinnati.

Fred B. Ely has gone to Europe for an indefinite period to engage in the examination of oil lands.

Vernon F. Marsters' office address is now 920 Grande Avenue, Hayes Building, 5th floor, Kansas City, Missouri.

The Australian Association meets in New Zealand next January.

The next meeting of the Pan-Pacific Congress is to be held in Australia, the Australian Government having voted $24,000 for the purpose.

Warren D. Smith, who has been for the past two years on leave of absence from the University of Oregon, in charge of the Division of Mines, Bureau of Science, Manila, P. I., returned October 1 to the University to resume his work in geology and geography.

Philip Andrews is at present connected with the Colorado Geological Survey. He was formerly on the engineering staff of the Eagle Picher Lead Company.

The American Association of Petroleum Geologists held a fall meeting in Denver, October 26, 27, and 28, where papers were presented covering an unusually wide range of subjects relating to petroleum geology.

Albert J. Walcott, a graduate of the University of Michigan, who has been carrying on research work in optical glass for three years with the Bausch & Lomb Optical Company, has been appointed lecturer in mineralogy at Northwestern University.

George Otis Smith has been appointed by the President a member of the United States Coal Commission.

J. B. Eby returned recently from his field work for the U. S. Geological Survey in the Wasatch Plateau coal field, Utah.

R. Van A. Mills is conducting field experiments upon the production problems in the Salt Creek oil field, Wyoming.

John M. Boutwell was married to Miss Ruth Crellin, daughter of Mr. and Mrs. Charles L. Crellin, at Pleasanton, California, on September twenty-eighth. They now reside at the Bransford, Salt Lake City, Utah.

Johnson, Huntley & Somers have dissolved their firm and Roswell H. Johnson will continue his practice at the Oil and Gas Building, University of Pittsburgh, Pittsburgh, Pennsylvania.

Bruce Rose, formerly a member of the Canadian Geological Survey and recently a member of the staff of the Whitehall Petroleum Corporation in India, has now joined the staff of the Departments of Geology and Mineralogy, Queen's University, Canada.

A. A. Baker has returned from field work for the U. S. Geological Survey in the Cold Bay petroleum district of Alaska.

Ira B. Joralemon has opened an office for practice as mining engineer and geologist at Room 1402, California Commercial Union Building, San Francisco, California.

Attention is called to the brief report on page 626 by R. A. F. Penrose, Jr., on the Thirteenth International Geological Congress held last August at Brussels, Belgium.

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